Macro Base Station Transceivers 2018

Abstract: This report provides a 5-year forecast for base stations, RRH units, and related radio transceivers for mobile communications. The forecast is broken down by band, by power level, by region, by MIMO configuration, by traffic density, by level of BBU integration, and by OEM market share. This year, we added a view of how much capacity (in Gbps) is shipped for each air interface)

February 2018

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MEXP-TRX-18

MACRO BASE STATION TRANSCEIVER FORECAST

February 2018

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EXECUTIVE SUMMARY

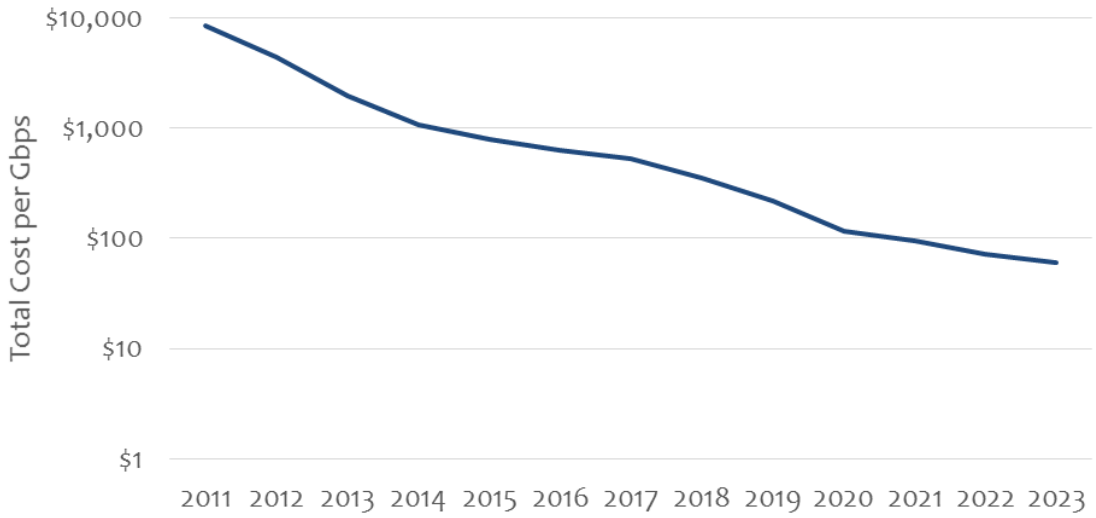
The mobile infrastructure market has shifted gears. For the past several years, the focus was on 4G/LTE deployment and 5G was a future possibility. During the past 12 months, 5G has become much more real. The first release of 5G NR standards is complete, the 5GTF trials are finished with at least 200 sites deployed in preparation for commercial launch, and many players are moving up their timescale for 5G.

We still see 2018 as a transition year, with weak revenue in the macro base station market and only the early-stage deployments for 5G. However, the rationale for investment in 5G has become more clear (see the Mobile Experts cost and ROI analysis in our 5G research). We now see a clear view from the CFO's chair that justifies a significant investment in 5G for Korean, Japanese, and American operators.

In the big picture, we believe that the mobile infrastructure market has reached a turning point. Everyone in the world with a reasonable income has a smartphone today. With LTE, the user can do anything on the Internet.

Now that smartphones can do everything that we do on desktop computers, we believe that the market will shift its focus. Instead of "new apps" driving the mobile infrastructure market, we believe that cost reduction in the operator network will be the primary focus of the industry in the future. Mobile data has become a commodity, and for every commodity cost takes the #1 priority.

Chart 1: Total Cost of Ownership Trend in Mobile Infrastructure , 2011-2023



Source: Mobile Experts. Cost figure represents the TCO for equipment deployed in the year shown.

China is gearing up to a huge 5G NR deployment that defies any rational view of capacity and speed requirements for users. The widely anticipated nationwide 5G roll-out at 3-5 GHz in China will dwarf the other deployments in Korea, Japan, and the USA. Because this is politically driven (as a jobs program and a vehicle to develop the Chinese telecom supply chain), the inherent risk in our China forecast is tremendous. We're anticipating a nationwide 5G surge in China—***but if the politics change, and an ROI-based approach is applied, then the Mobile Experts forecast for 5G NR deployment would quickly drop in half or more.***

Outside of Asia and the United States, we expect 5G NR deployment only in selected countries where operators have very high data density and high ARPU. In European countries such as Finland and the UK, we expect spotty 5G deployment in cities with base station numbers that are pretty small compared with Asia and the USA.

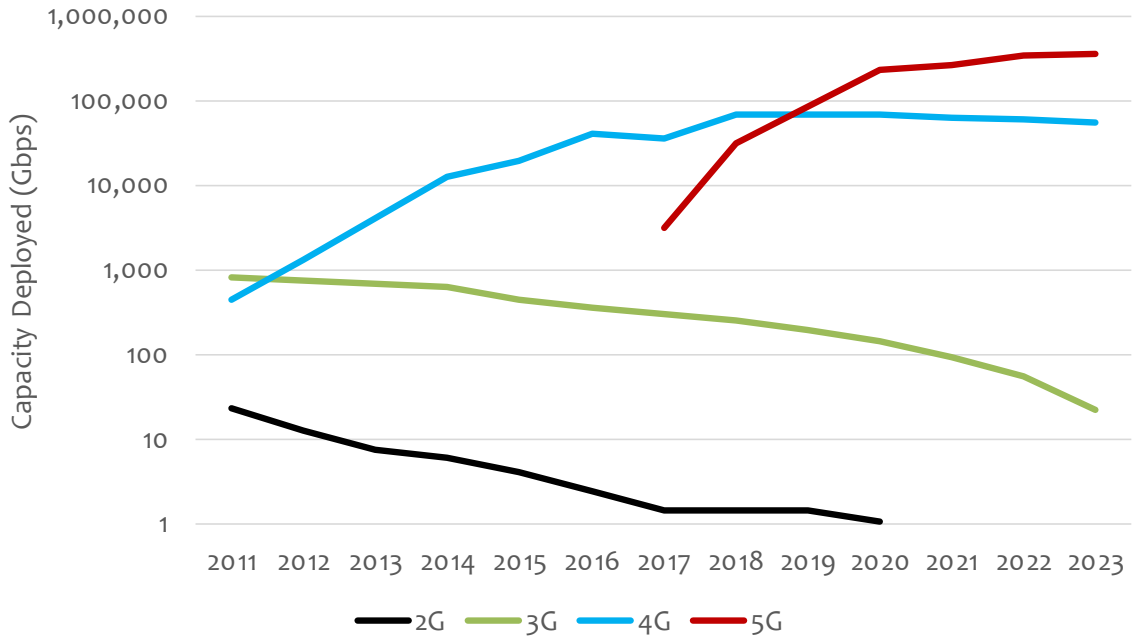
LTE capacity buildout will continue throughout our five-year forecast window, and we also expect ongoing deployment of NB-IoT base stations for companies like Dish Networks and mobile operators without modernized GSM hardware.

A few technical trends are important to watch:

1. Massive MIMO is now in the field and working for TD-LTE networks. This feature will be used in a few FDD cases (not many), and in a large proportion of the 5G NR deployment.
2. 5G NR deployment will be strongest at 3-5 GHz, but fixed and mobile 5G networks at 28-40 GHz will also be deployed with very high capacity. The complexity of millimeter-wave networks will be high, with 256T256R systems likely (using four panels of 64T64R each).

Based on these technical trends, the 5-year outlook for radio transceivers includes significant opportunities. The large capacity of fixed-wireless 5G deployment will drive significant capacity, so despite small numbers of base stations the mm-wave deployment of a few operators can be significant in terms of actual traffic. In addition, the large size of the Chinese deployment will drive a rapid rise in capacity available in Asia.

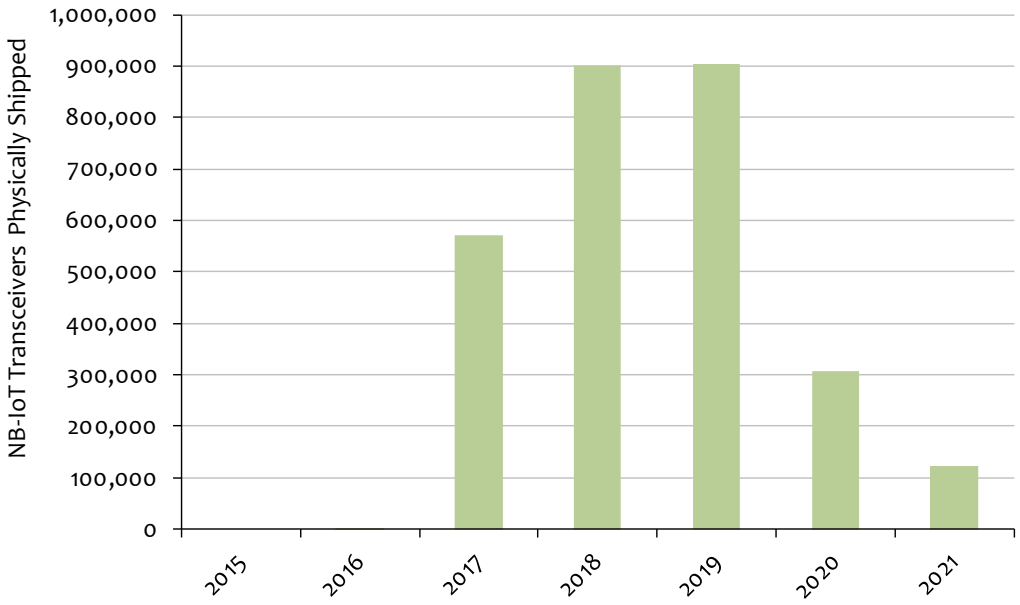
Chart 2: Capacity deployed , 2011-2023



Source: Mobile Experts.

In total, we expect rising numbers of transceiver shipments, as M-MIMO and TD-LTE systems continue to drive larger numbers of transceivers per base station. With significant changes in the number of radios and the physical form that some radios will take, we see growth opportunities for RF hardware and baseband capacity.

Chart 3: Forecasted Macro Base Station Transceiver Shipments by generation, 2016-2023



Source, Mobile Experts.

SECTION 1: BASE STATION FORECAST

Macro Base Station Forecast

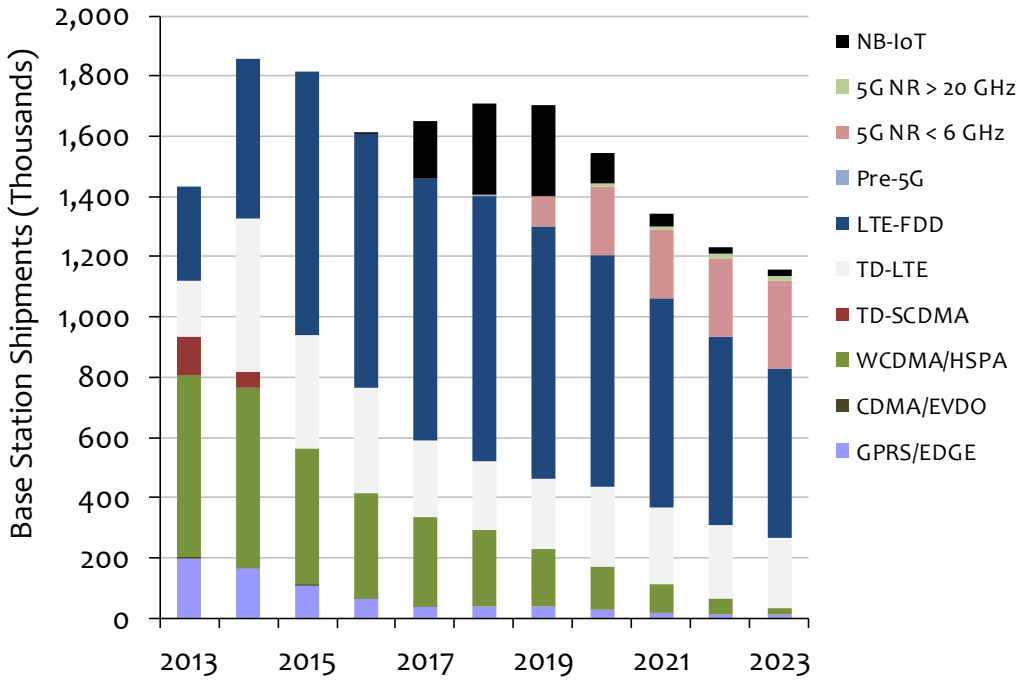
Mobile Infrastructure is mature and we have solid 2G/3G/4G coverage for almost every location where consumers are willing to pay a reasonable ARPU for services. We've passed the peak of the LTE market and now we're starting to see 5G plans coming together for the leading operators.

Over the next five years, four new trends will dominate the market for macro RAN infrastructure:

- LTE will continue capacity upgrades. Not all locations have 3-4 frequency bands in operation, so the main bulk of market shipments will be oriented around filling in LTE capacity.
- 5G NR deployment will take off at 3.5 and 4.5 GHz. In some cases these deployments will be huge (China), and in other cases the deployment will be measured based on capacity and hotspot requirements (Europe).
- RAN infrastructure will be deployed for both fixed-wireless (Verizon) and mobile wireless applications (SKT, KT, AT&T) at 24-28 GHz. The economics are not driving these operators toward nationwide deployments… instead these will be very highly targeted urban deployments.
- NB-IoT base stations are in deployment now, as operators such as China Mobile, China Telecom, and others find a need to deploy new hardware. Most other operators will be using their existing hardware with a software upgrade, so this segment is limited.

Note that in the actual market, the definition of a "base station" has lost its meaning. In the past, a base station was clearly a cabinet that included both radio units and digital baseband processing. That configuration is not used in most cases today. Mobile Experts has continued to track the number of "base stations" deployments because many customers continue to use this terminology. To be clear, in our forecast the term "base station" refers to a single site with three or more radio units and the supporting baseband capacity (which is typically deployed in a centralized data center).

Chart 4: Forecasted Macro Base Station Shipments, 2013-2023



Source, Mobile Experts. Note: Definition of base station is RRH units and BBUs.

Centralized Base Stations and Compact BTS

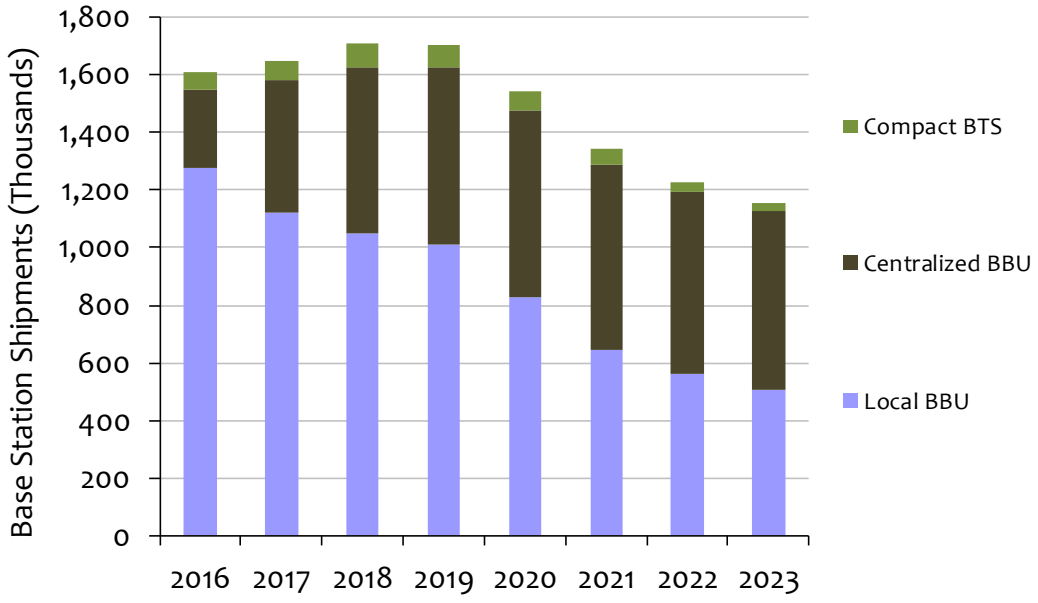
We track three different classes of Macro Base Stations: The traditional base station where the baseband unit is located at the site, base stations with centralized BBUs, and "compact BTS" architectures where the BBU and the radio unit are integrated. The majority of sites continue to use the traditional approach, but centralization and "compact BTS" formats are growing now.

Leading LTE operators are almost all moving to the Centralized RAN concept, as a step toward a Virtualized RAN that can be migrated to 5G over time. This direction is well understood and the use of CPRI-based RRH units has already been taken by most leading operators, especially in high density markets such as Japan, Korea, and USA.

Split-baseband RRH deployment will also be a useful step toward making a Centralized RAN affordable, so we include both the CPRI format and alternative split-baseband formats in our forecast for "Centralized" deployment.

Compact BTS architectures are used in cases where Centralized RAN is not used, such as rural cases or low cost markets without centralized coordination. Overall this architecture represents a smaller segment of the overall LTE market.

Chart 5: Base Station Shipments, Local vs Centralized vs Compact, 2016-2023



Source, Mobile Experts

Multi-mode Base Station Architecture

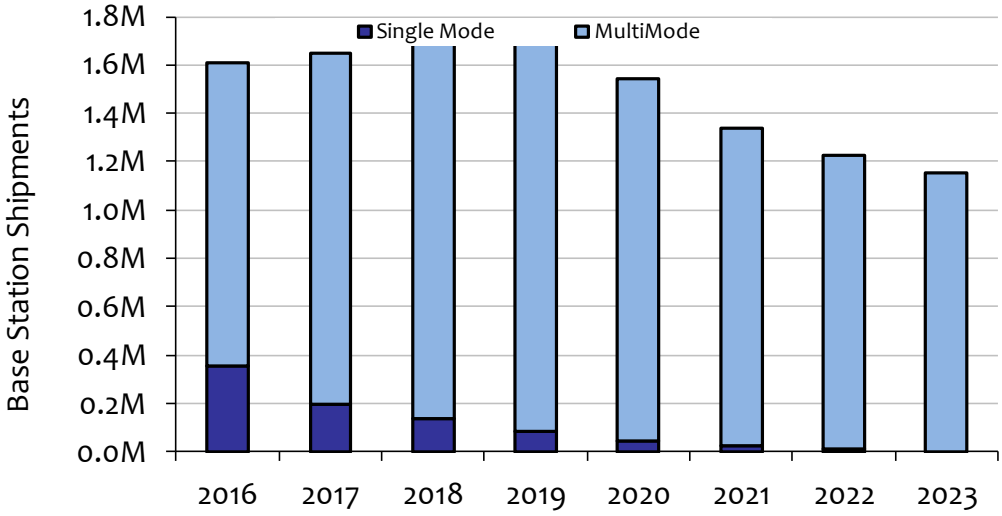
Mobile Experts started tracking multi-mode architectures in the 2004 timeframe, and we've watched this architectural concept take over the entire market. During the next five years, we expect single mode base stations to continue to decline, as single-mode GSM and low-cost versions of other base stations are not expected to be competitive when compared with flexible multi-mode designs.

The uncertainty of future waveforms and the desire for a common hardware platform are two very clear drivers for OEMs to move toward multi-mode RRH and BBU capability. We don't see this trend turning around.

Notably, there was some discussion about a return to "single mode" optimized base station hardware in order to have specialized low-cost platforms for cases such as IoT. However, the introduction of NB-IoT drives an ongoing need for flexibility in the RF carriers that has been proven to work best on the multi-mode platform. At this

point, it's clear that all base station development moving forward will use programmable logic for multimode operation.

Chart 3: Base Station Shipments, Multimode vs. Single mode, 2016-2023

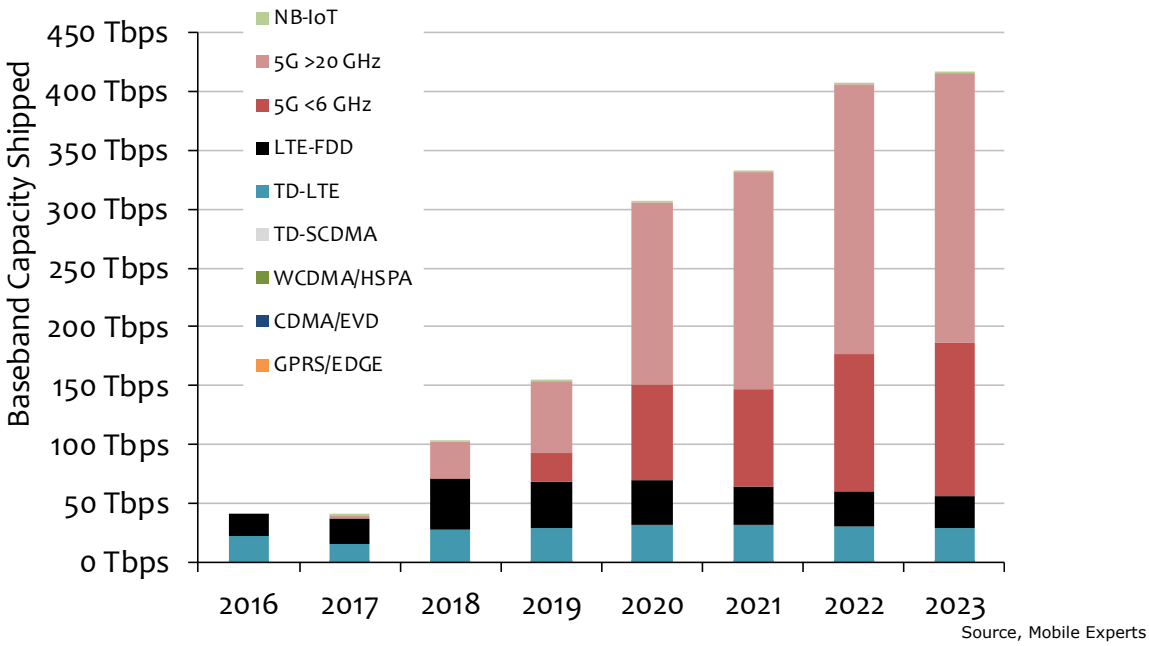


Source, Mobile Experts

Baseband Capacity Deployed

While the number of base stations deployed each year is shrinking, the raw capacity offered by each base station is growing quickly. The move to Massive MIMO, with higher spectral efficiency in wider channels drives a huge expansion in the capacity for each radio. Amazingly, during 2019, we expect 5G to overtake LTE in terms of the Pbps of capacity that are actually shipped!

Chart 3: Base Capacity Shipped in Tbps, by air interface, 2016-2023



Traffic Density in the Network

The Macro network is no longer a stand-alone network layer. Almost all major LTE networks have small cell elements incorporated today. The use of a HetNet architecture is strongly correlated with the density of traffic in the network, so Mobile Experts has created a tracking metric to track mobile traffic density in networks, measured by Gbps of traffic per square kilometer per MHz of licensed spectrum. (Gbps/km2/MHz or GkM).

This year, Mobile Experts is also setting a tentative threshold where we expect Massive MIMO to come into the network. For networks at GkM below about 0.05, Massive MIMO is too expensive and not necessary. However, at GkM levels of about 0.12 and higher, Massive MIMO becomes necessary to avoid excessive investment in ridiculous numbers of small cells.

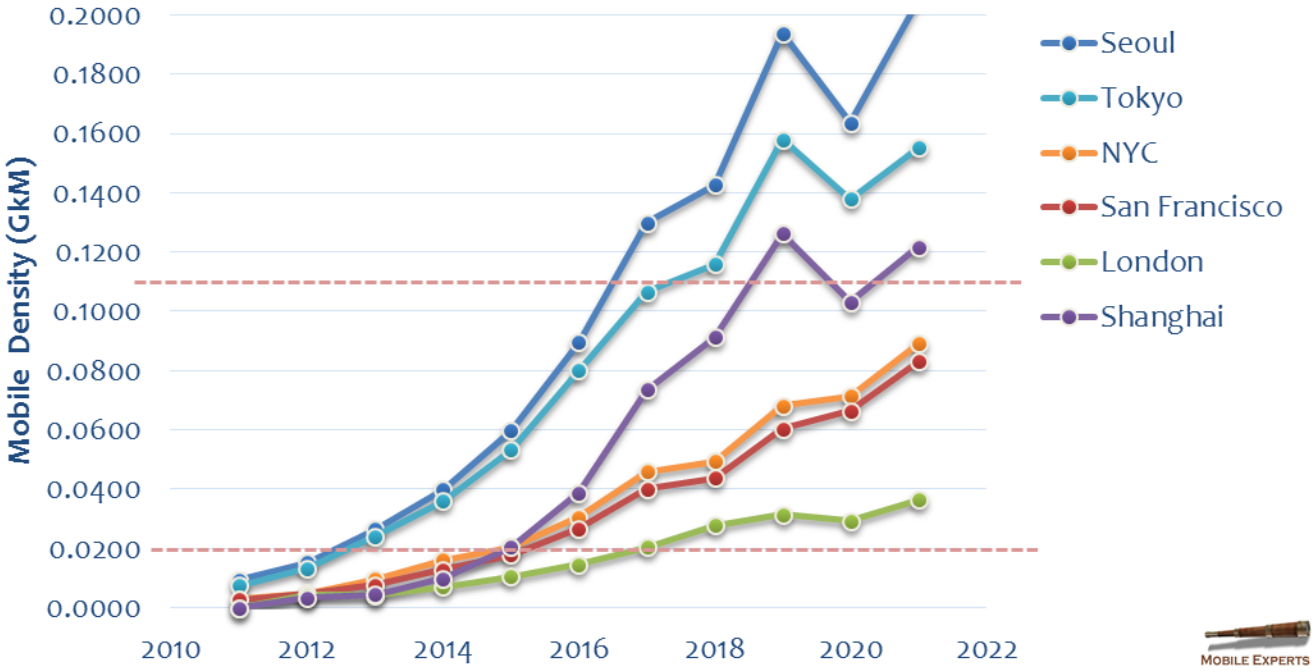


Figure 1. Traffic Density for various world cities and expecting timing of Massive MIMO

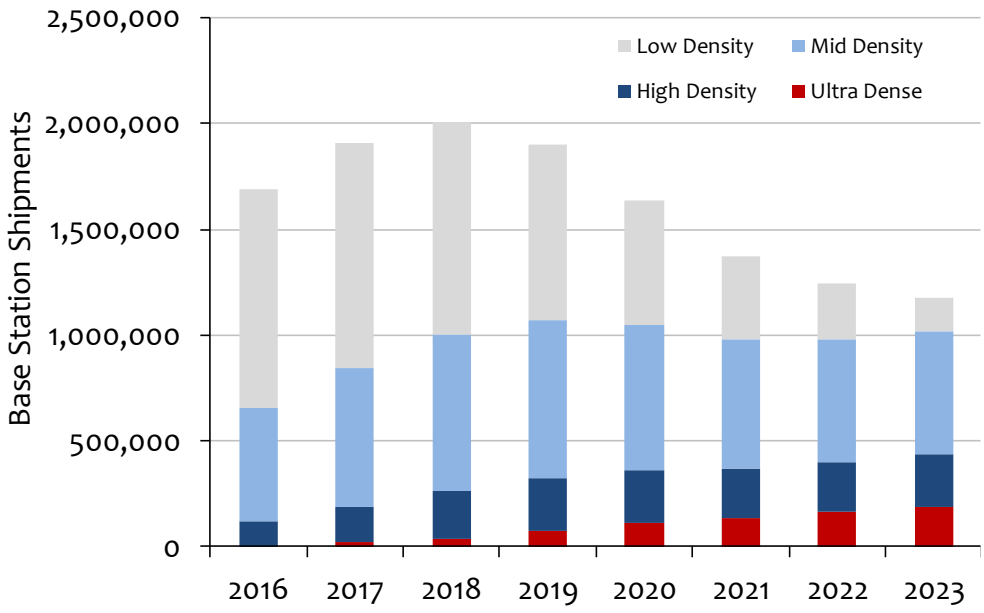
Source: Mobile Experts

Examples of high traffic density take place in subway stations and other crowded locations in Tokyo and Seoul, exceeding 0.1 GkM for several hours every day. Western cities such as New York have about half the mobile density of Tokyo and Seoul, so we expect Massive MIMO to come later in the US mobile market.

To best utilize this metric, we segment our Base Station forecast into four parts:

- Base stations deployed in "Ultra dense" networks experience traffic density higher than 0.1 GkM at peak hour.
- "High density" locations handle traffic density higher than 0.02 GkM or 20 MkM. (Mbps/km2/MHz) In other words, these are base stations in areas where small cells, DAS, or heavy Wi-Fi offloading will also be utilized.
- "Mid Density" roughly corresponds with suburban areas where traffic density is between 5 MkM and 20 MkM.
- "Low Density" typically means rural installation, where traffic density is lower than 5 MkM.

Chart 6: Base Station Shipments, by density of traffic, 2016-2023

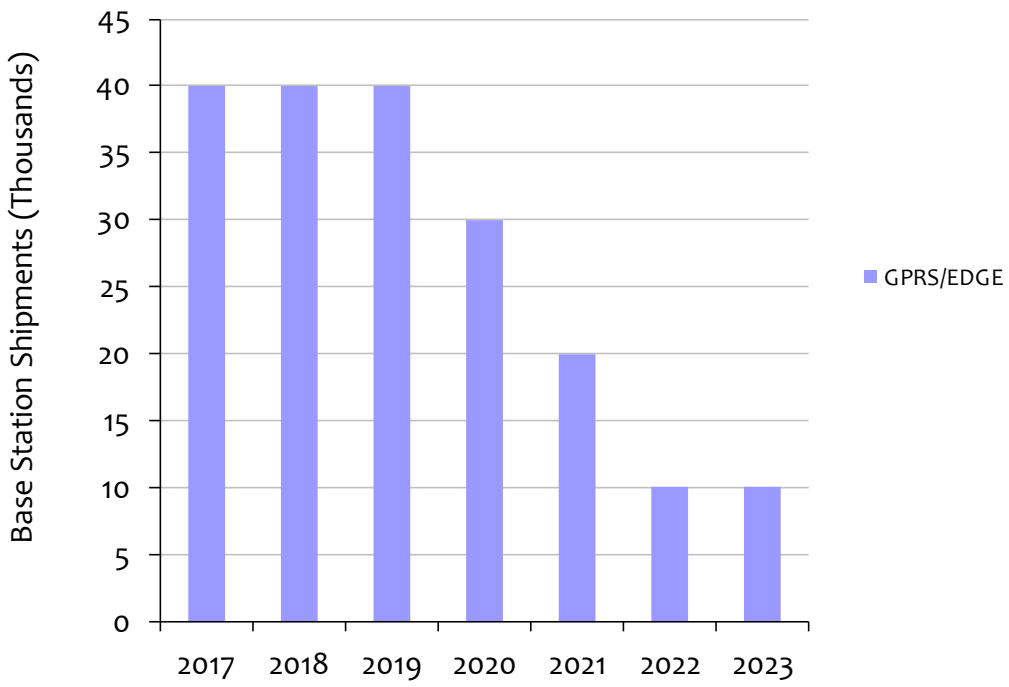


Source, Mobile Experts

GPRS and EDGE

The 3GPP standards committees have recently updated GSM/GPRS standards to optimize for IoT applications, with multiple retransmissions and long sleep cycles. However, we don't expect this to drive significant new deployment. GSM and EDGE deployment is declining, as it's focused on poor areas of Africa, India, and elsewhere in South Asia. The main reason that this continues is that low-cost GSM handsets are the best option in these poor areas, for simple long-range voice connectivity and low-cost infrastructure. For those applications, predict small numbers of shipments well into the 2023 timeframe. Cheap base stations are a big part of the ongoing story here, with compact BTS designs (including radio, baseband, BSC, and even core network elements) in a small box for less than $3,000.

Chart 7: GSM Base Station Shipments, 2016-2023

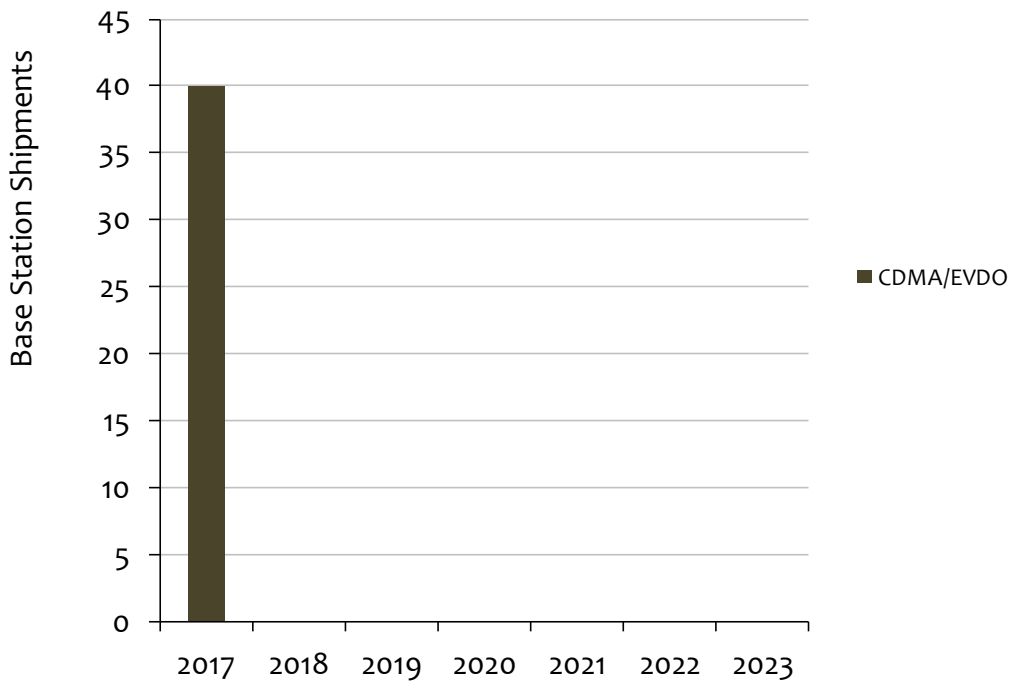


Source, Mobile Experts

CDMA

Qualcomm's CDMA standard is reaching the end of the road. Almost all major CDMA operators worldwide currently planning its replacement with LTE. Very few new base stations will be deployed in 2018-2020, and in fact we're starting to see the end of capacity upgrades so we've zeroed out our forecast for 2018.

Chart 8: CDMA Base Station Shipments, 2016-2023



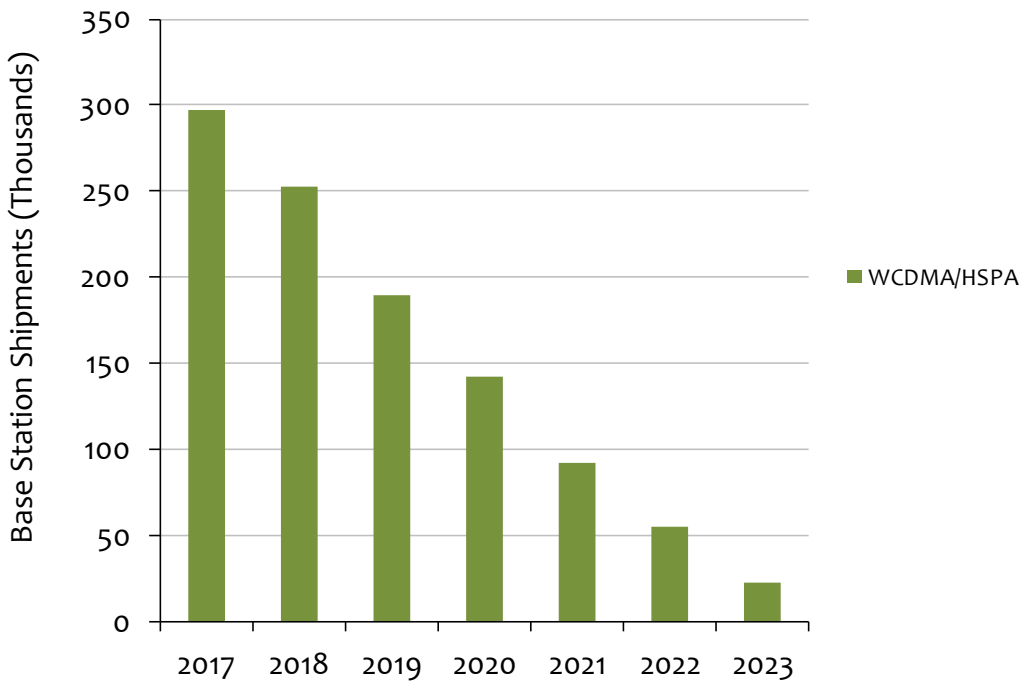
Source, Mobile Experts

WCDMA and HSPA

HSPA/WCDMA base station deployment is steadily declining, as LTE is taking over in most of the Eastern European and Asian markets where 3G was stronger in 2016. Some network deployment that was started in South Asia, Africa, and Latin America still needs to be completed, but we don't expect any new surges in capital spending here.

As with GSM Compact BTS architectures, we can expect some long-term rural sales of compact HSPA base stations… but the numbers will be small at only a few thousand per year.

Chart 9: WCDMA Base Station Shipments, 2016-2023



Source, Mobile Experts

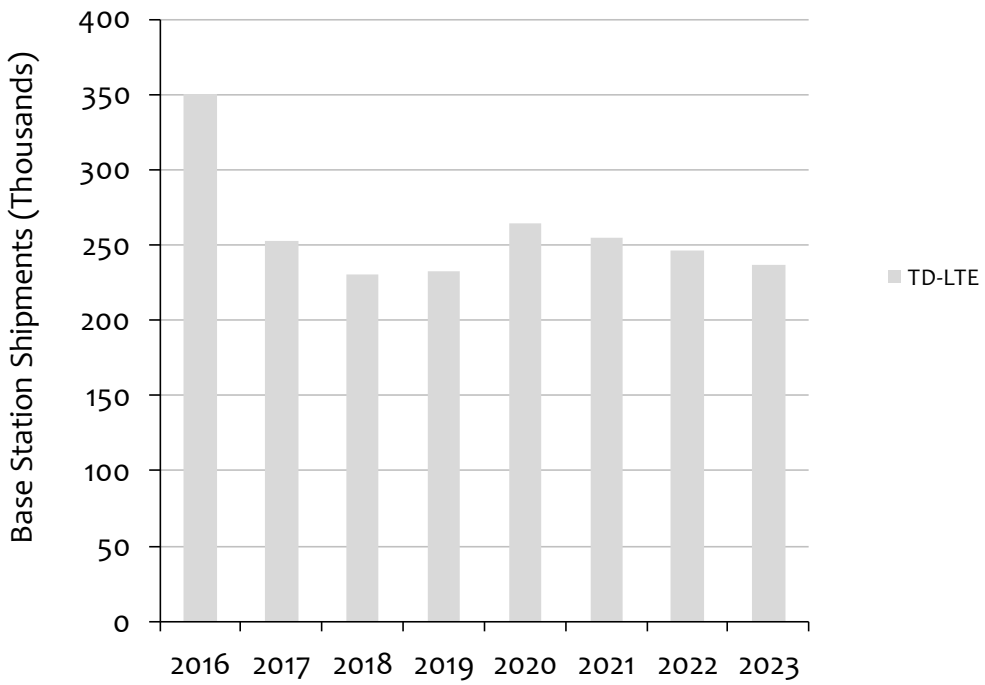
TD-LTE

The peak for TD-LTE deployment was in 2014-2015, when China Mobile deployed huge numbers of base stations nationwide. Today, China Mobile, Softbank, Sprint, Jio, and a few other operators dominate the market for TD-LTE. These big operators are shifting to upgrades of the radio to utilize Massive MIMO, and at the same time are slowing down on spending for new site deployments. They're also deploying additional radio carriers to fully utilize the wide 2.5 GHz spectrum blocks, where in some cases they're not fully utilizing the spectrum today.

Smaller operators will deploy TD-LTE as they acquire the rights to spectrum and as customer demand in less developed countries justifies the high-band LTE deployment. We expect a long-term market for TD-LTE deployment in India and APAC, in areas that are dominated by 3G coverage today.

Deployment in the 3.5 GHz bands is starting to shift to 5G NR with larger operators, so we don't expect the TD-LTE market to see a surge of investment there.

Chart 10: Forecasted TD-LTE Base Station Shipments, 2016-2023

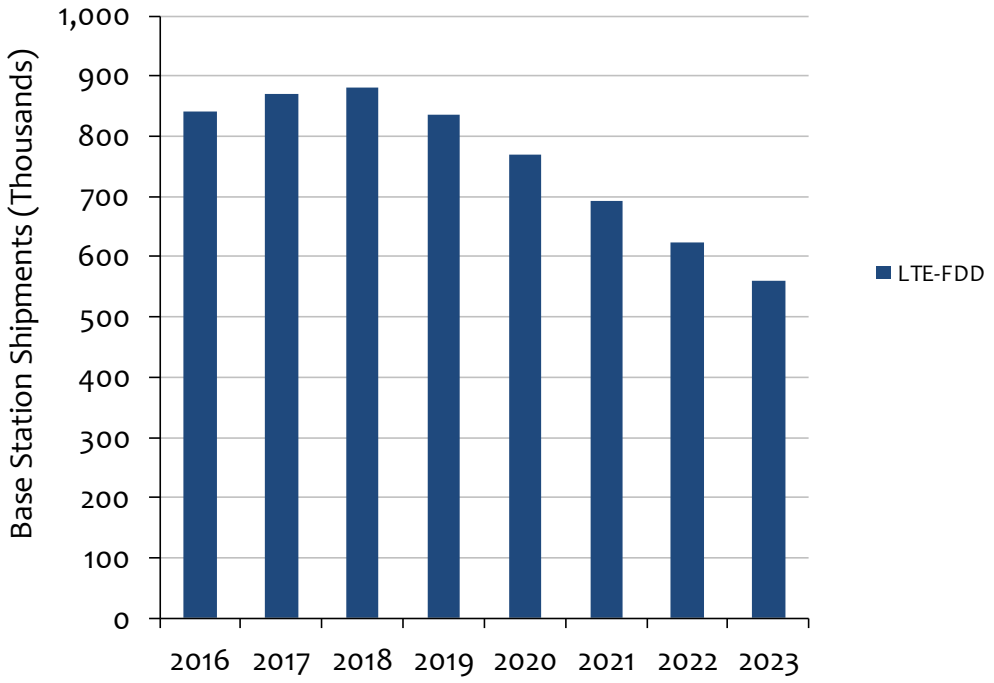


Source, Mobile Experts

LTE-FDD

In the FDD bands, LTE deployment is continuing. Many operators have only deployed 10-20 MHz LTE channels, but can upgrade to 40 MHz or more by adding adjacent RF carriers. We expect this capacity upgrade cycle to continue for FDD based bands, as 3G and 2G systems are eventually removed to make room for LTE and its higher spectral efficiency.

Chart 11: LTE-FDD eNodeB Shipments, 2016-2023



Source, Mobile Experts

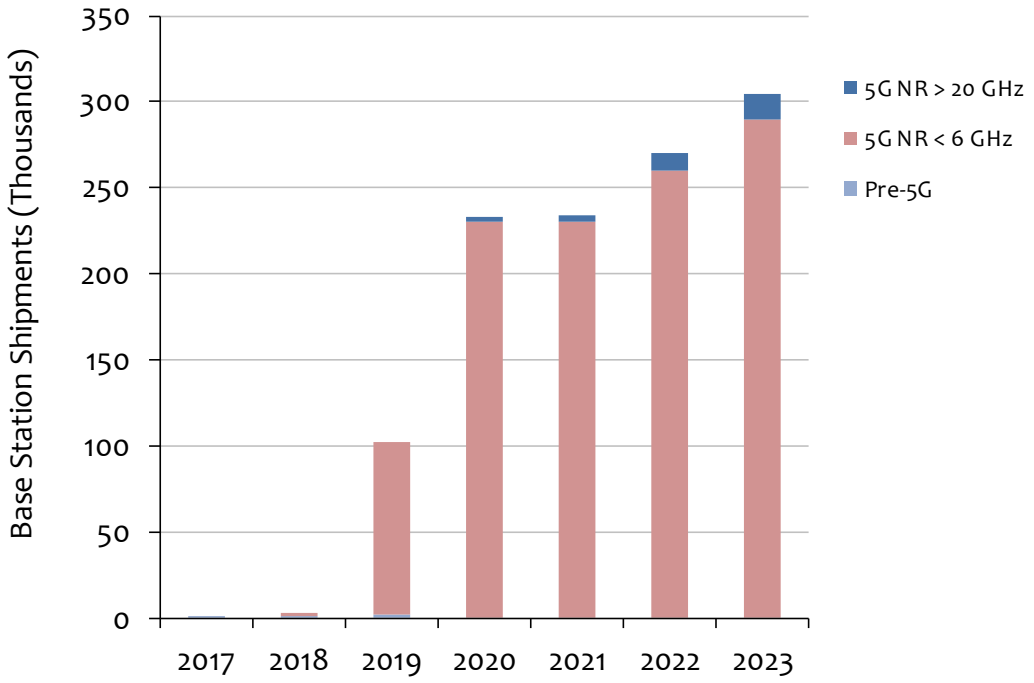
5G NR

During 2017, pre-5G deployment took place with fixed wireless equipment in the USA and some trial equipment in Korea for the Olympics. Both of these networks were too early to use the "5G NR" format that was finalized by 3GPP in December 2017. We expect that by 2020 all of the base stations deployed under the 5G category will use the 3GPP standard waveform.

Deployment will continue at a very small level in 2018, with Verizon dominating the shipments in their drive to cover three US cities at 28 GHz. Other networks will be working on a reset to the 5G NR format.

During 2019 and 2020, we're predicting large "field trial" quantities for China Mobile as well as China Telecom/Unicom at 3.5 to 4.5 GHz. The details are still fuzzy here, but Mobile Experts has taken a conservative view with 30,000 sites spread over these two years. These quantities will expand dramatically in 2021 as the Chinese operators will be barreling forward with nationwide 5G deployments.

Chart 12: 5G NR "Base Station" Shipments, 2016-2023



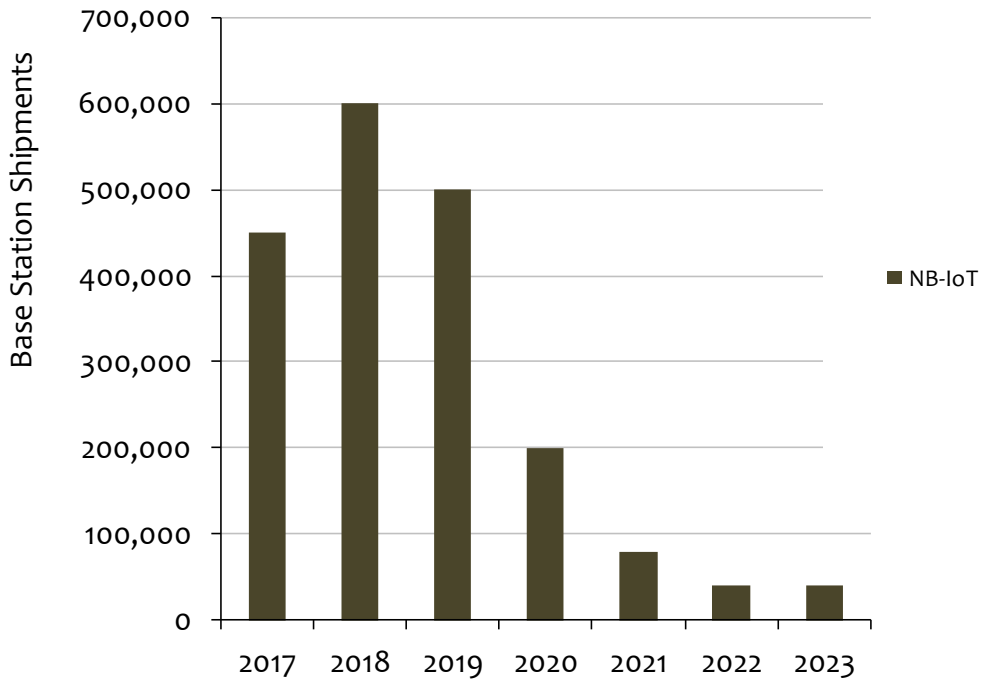
Source, Mobile Experts

NB-IoT

Most of the LTE Category M networks and NB-IoT network hardware is already in the field, to be lit up via software upgrade. But there are cases emerging that require hardware deployment. China Telecom and China Mobile are the largest examples today, where existing network equipment at 800-900 MHz was not capable of the upgrade to a 900-NB-IoT network.

We expect other examples like this to pop up in Latin America, Eastern Europe, and APAC where older GSM equipment is simply not capable of the NB-IoT waveform. Larger deployments should be completed by 2020, but this class of operators will buy some NB-IoT base station equipment for about 10 years to come at a low level.

Chart 13: NB-IoT New Base Station Hardware Shipments, 2016-2023



Source, Mobile Experts

SECTION 2: TRANSCEIVER FORECAST

While the Base Station forecast is always listed first in our analysis of the Macro market, Mobile Experts actually focuses much more intently on radio transceivers as our primary metric for hardware shipments. The definition of a "base station" is pretty fuzzy now that RRH units and baseband processing are in two different locations. Mobile Experts defines a transceiver as a single RF transmitter chain and its associated receiver chain(s), including the electronics from the ADC/DAC through the power amplifiers and duplexers that feed the antenna. With Massive MIMO, this means that the number of radio transceivers can get enormous very quickly.

Looking at the details of the transceiver, it's clear that 2017 radios are very different than the radios shipped in 2007 or 1997. The average power level has dropped as we have moved from SISO to 2x2 MIMO and now 4x4 MIMO. The bandwidth has increased dramatically. And these trends will continue.

LTE infrastructure market has now clearly passed its peak. Leading operators have deployed LTE in three or four frequency bands, allowing them to reach gigabit speeds. LTE deployment continues with operators filling in additional carriers to utilize the full spectrum band….but the big surge related to nationwide deployments has now passed.

As the LTE network is upgraded for capacity, some sites will need Massive MIMO, and other sites simply need a radio with wider bandwidth or more power for an additional RF carrier. Most LTE upgrades will fall in the latter category, as LTE Massive MIMO will only pay off in cases with wide bandwidth and very high traffic demand.

Looking ahead to 5G, we can expect the surge of deployment at 3-5 GHz to be significant. China represents most of our forecast through 2023, due to the strong government-led support for 5G deployment through all three mobile operators. Other countries will be deploying 5G more slowly, with 5G coverage overlaid on top of LTE in cities that have high traffic density.

Mobile Experts breaks down the transceiver forecast in multiple dimensions:

- Upgrades vs. New Deployment
- Breakdown by transceiver complexity (2T2R, 4T4R, through 128T128R)
- Breakdown by MIMO level
- Number of Physical RRH units shipped
- Number of Active Antenna Systems and beamforming elements
- Breakdown by RF power level
- Breakdown by region

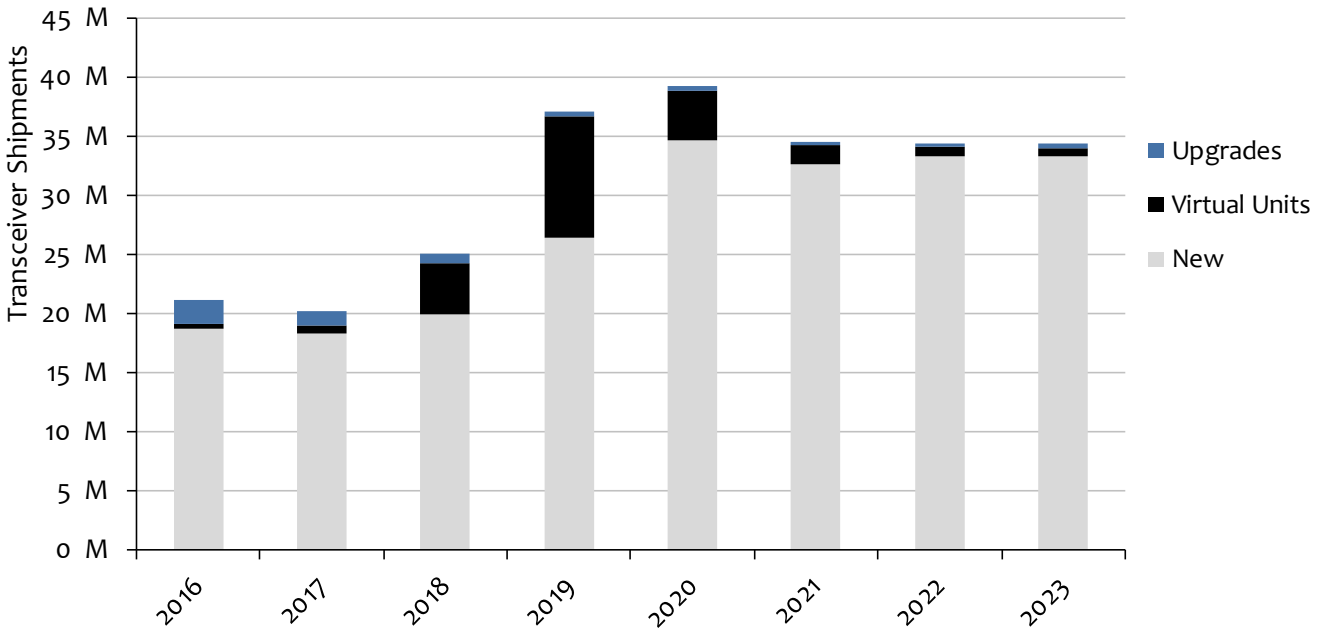
- Market share by OEM

Transceiver Upgrades

Radios break down, so any mobile network needs spares and replacements to replace about 1% of the active network every year. Roughly 6% of transceiver shipments in 2017 were used as upgrades or replacements. Mobile Experts counts several types of radio shipments in the "upgrade" category, generally defined as a shipment of a new radio where the baseband processing is unchanged:

- Transceivers fail at about 0.5% to 1% per year, so new units are installed to replace failed units.
- MIMO upgrades require additional transceivers.
- Boosting the power level in a macrocell may involve replacement of the transceiver board or RRH.
- An LTE channel deployed at 10 MHz may migrate to 20 MHz or wider, requiring new radio hardware to accommodate the wider channel. Intra-band Carrier Aggregation is a prime example of how a wider channel bandwidth would be required.
- Upgrade to Massive MIMO entails replacement of the RRH and antenna, to replace with an integrated antenna radio unit. Many of these upgrades in LTE systems are listed as new deployments because the BBUs are replaced.
- NB-IoT hardware deployments are not counted here because both RRH and BBU are impacted.

Chart 14: Transceiver Shipments, Upgrades vs. Virtual vs. New Units, 2016-2023



Source, Mobile Experts

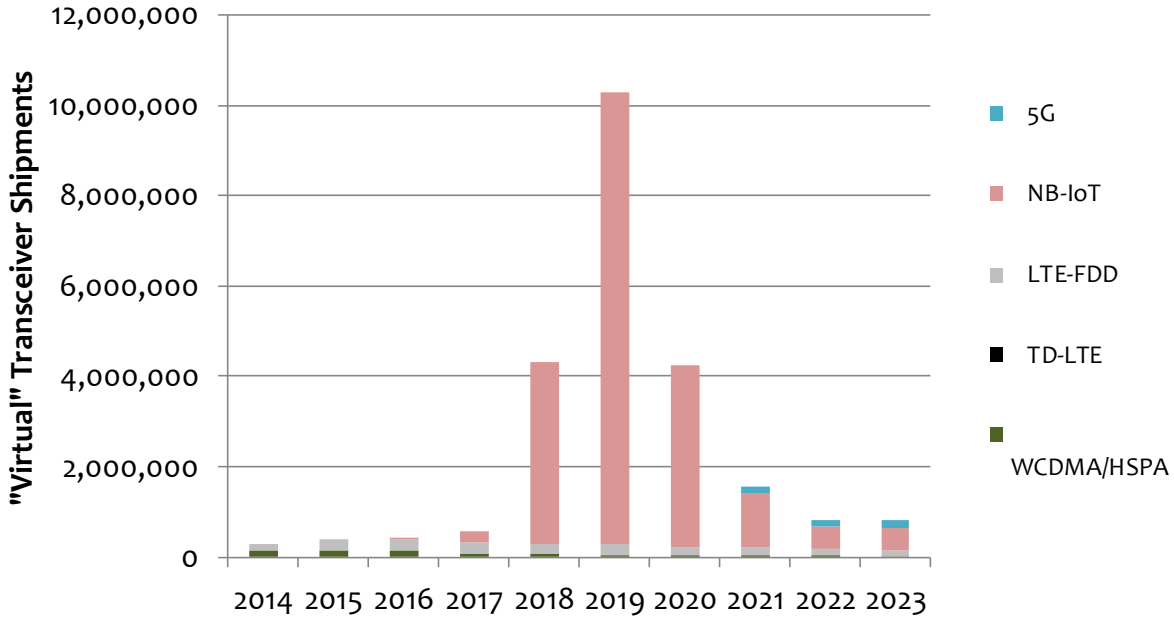
Software Upgrades: "Virtual" Transceiver Shipments

To keep accurate records, Mobile Experts records the number of "transceivers shipped" through software upgrades instead of physical transceiver units. Note that these units are NOT included in the other charts, so this category is shown for illustration only. (Note the large numbers of NB-IoT upgrades via software)

In theory, the OEMs are selling hardware that is completely future-proof and all upgrades will be done through software. But this does not work out in the real world. Operators wind up buying new radio hardware for multiple reasons:

- Different frequency bands or wider bands are used for new network changes.
- The CPRI or OBSAI interface on the original equipment is too slow for a high-bandwidth LTE signal.
- The original 3G radio was deployed without MIMO transmitters, or the original 2T2R LTE deployment must be upgraded to 4T4R or higher.
- The base station platform has changed in form factor.
- The peak power of the waveform increases as we move from 3G to LTE to 5G NR, requiring new amplifier components.

Chart 15: "Virtual" Transceiver Shipments, by air interface, 2014-2023



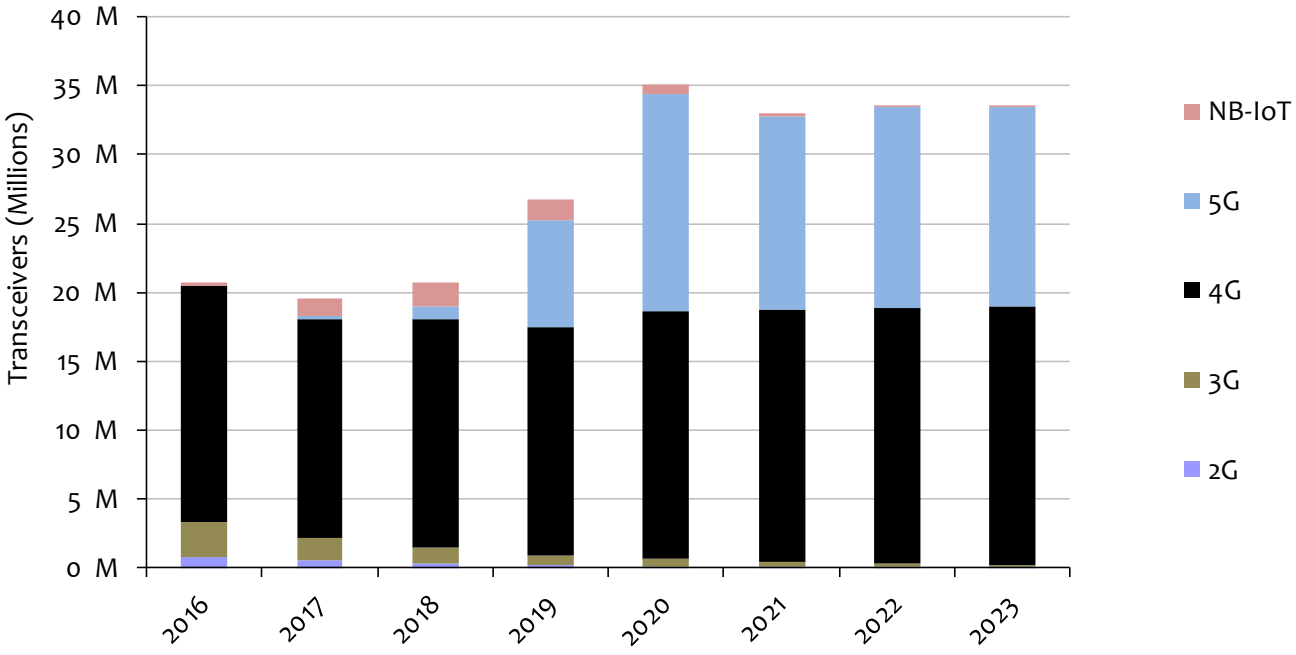
Source, Mobile Experts. Note: These units are NOT counted in Mobile Experts transceiver forecast totals.

Total Transceiver Shipment Forecast

While the LTE base station forecast is trending downward, the number of transceivers shipped for LTE is still increasing. New deployment of NB-IoT and 5G networks are increasing the number of radios dramatically as well. One driving force here is that 64T/64R complexity will start to drive huge numbers of radio paths. The rise of Massive MIMO will change everything, as the power levels, construction techniques, cost profile, and other aspects of the RRH will be completely different in the future.

The expected decline for 2017-2018 has been offset by massive deployment of NB-IoT base stations in China. Looking only at the 2G-4G market, it's clear that the market is down for 2017 and 2018, but the number of NB-IoT transceivers has been a nice cushion and 5G is starting to heat up.

Chart 16: Transceiver Shipments, by generation, 2016-2023



Source, Mobile Experts

Looking a bit closer at the transceiver market by specific air interface, we see that TD-LTE is responsible for the biggest drop in radio shipments during the past year… the surge of deployment in China is impossible for anyone else to sustain. There is reasonable TD-LTE deployment by other operators in the APAC region but nothing compares with the 10-15M per year numbers for China Mobile in 2014-2015.

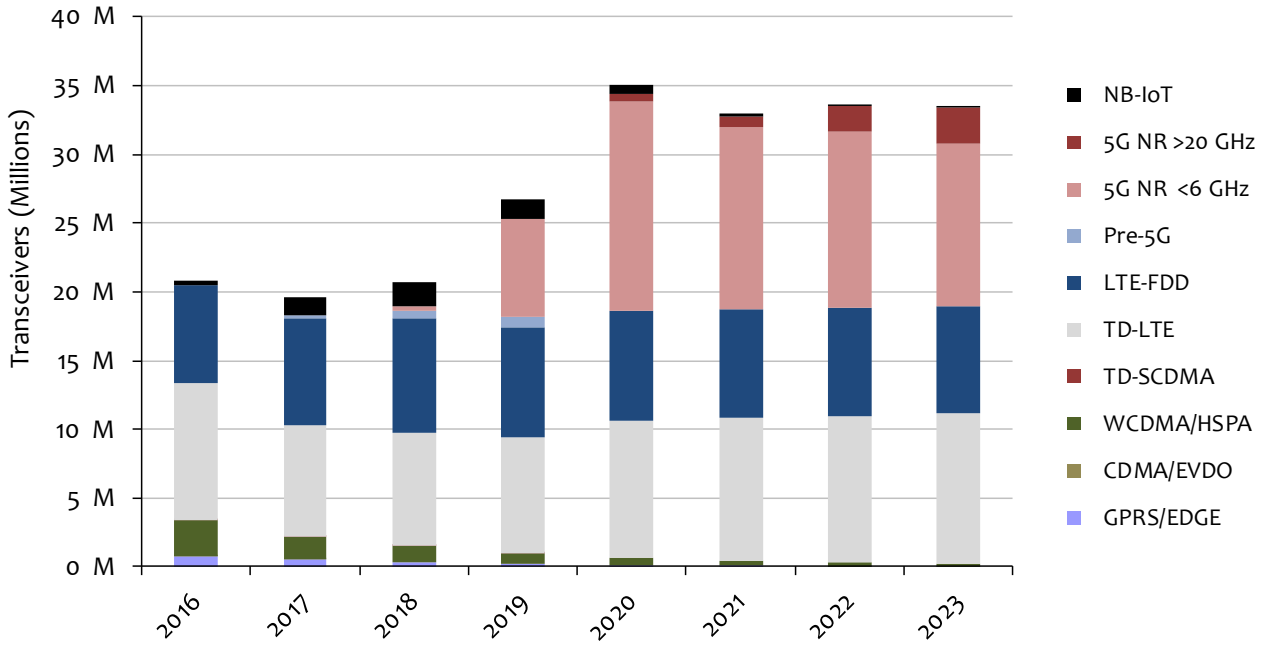
FDD-based LTE is continuing along, with an eventual decline after 2018, essentially following the traditional slow decline that we've seen before for 2G/3G equipment. Radio transceivers are expected to peak in 2018 due to the rise of 4T4R shipments (which effectively double the transceiver count for each base station shipped).

Looking forward to 5G, we've chosen to show the forecast by 5G NR transceiver shipments below 6 GHz and above 20 GHz. Nearly all of these will be TDD based for the next few years (except for specific networks such as T-Mobile USA). The vast majority of 5G deployment through 2023 will take place at 3.5 to 4.5 GHz, led by the three Chinese operators with expectations of a massive nationwide rollout.

The growth of 5G in the mm-wave bands will be slower and more incremental, as this level of deployment will only take place in locations that need very high traffic density.

GSM will continue at a low level through 2023 but we are seeing the end of CDMA and WCDMA.

Chart 17: Transceiver Shipments, by air interface, 2016-2023



Source, Mobile Experts

Transceiver Shipment Breakdown by Complexity (Massive MIMO) Level

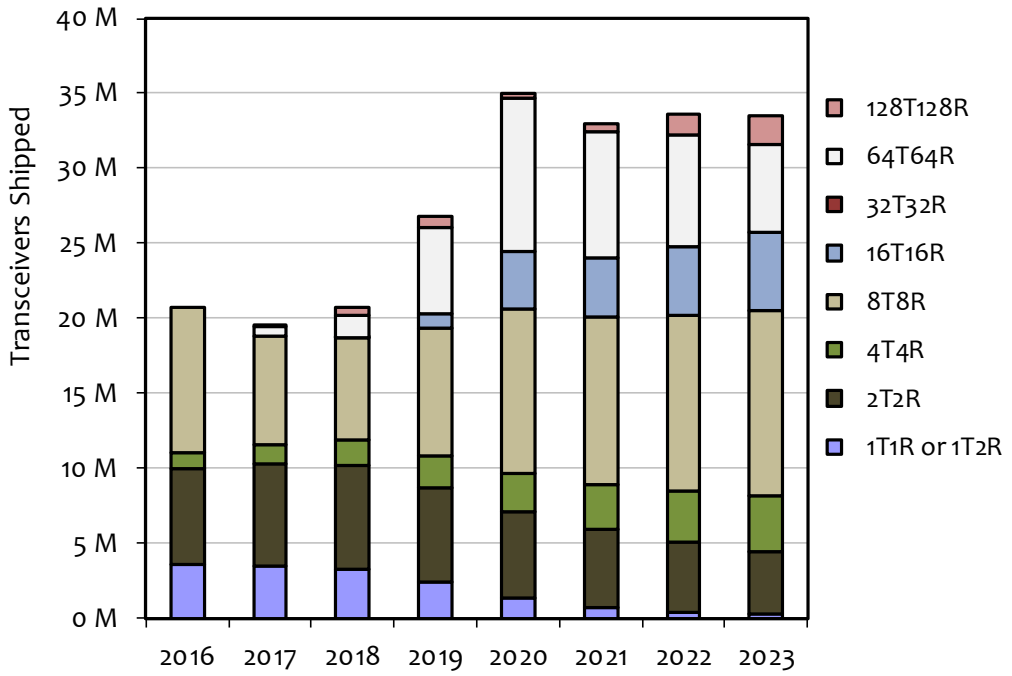
Massive MIMO has been introduced to the market with a few thousand base stations in TD-LTE and successful field trials in LTE-FDD. Of course, a large percentage of the 5G NR market will also use Massive MIMO in multiple different configurations. The complexity of a typical radio is steadily increasing:

- The SISO category (with either 1T1R or 1T2R radios) is becoming dominated by NB-IoT deployment, with very small numbers in the leftover 2G/3G market.
- 2T2R is declining, as most new deployment for LTE-FDD is 4T4R.
- The 4T4R market looks to be mostly FDD-based. There is a possibility that 5G NR will be deployed in TDD bands in a 4T4R configuration, but guidance from China is that their networks will be 8T8R as a baseline configuration, to match the CMCC LTE network.
- Either 16T16R or 32T32R will be used in some cases for 5G NR deployment. We are currently projecting the 16T configuration for the highest possible

amplifier efficiency, but this could change for the suburban 5G NR application to a 32T configuration for more steering.

- The 64T and 128T levels will be a common configuration for urban 5G NR deployment as well as the TD-LTE upgrades over the next few years. It's possible that multiple radio units at 128T128R will be combined in a single sector, but we don't expect any radio products to be constructed at a 256T or higher configuration. It's more likely that two 128T products or four 64T products would be mounted together.

Chart 18: Transceiver Shipments, by Massive MIMO level, 2016-2023



Source, Mobile Experts

SECTION 3: MIMO and MU-MIMO FORECAST

MIMO (Multiple Input, Multiple Output) boosts capacity and makes the link more robust, and almost every 4G and 5G implementation uses MIMO at some level.

Multi-User MIMO appeals to operators as well, because MU-MIMO can provide higher capacity for the network by offering separate streams for individual users.

It's important to note that MIMO level, transceiver complexity, and beamforming are three completely separate variables. Massive MIMO systems are in deployment today with 128 antenna elements, fed by a 64T64R radio subsystem, and running 16 beamsteering elements. This kind of hardware might support either 8 or 16 MIMO streams.

It's confusing for many people, so this forecast attempts to clarify the confusion by providing separate analysis for each dimension.

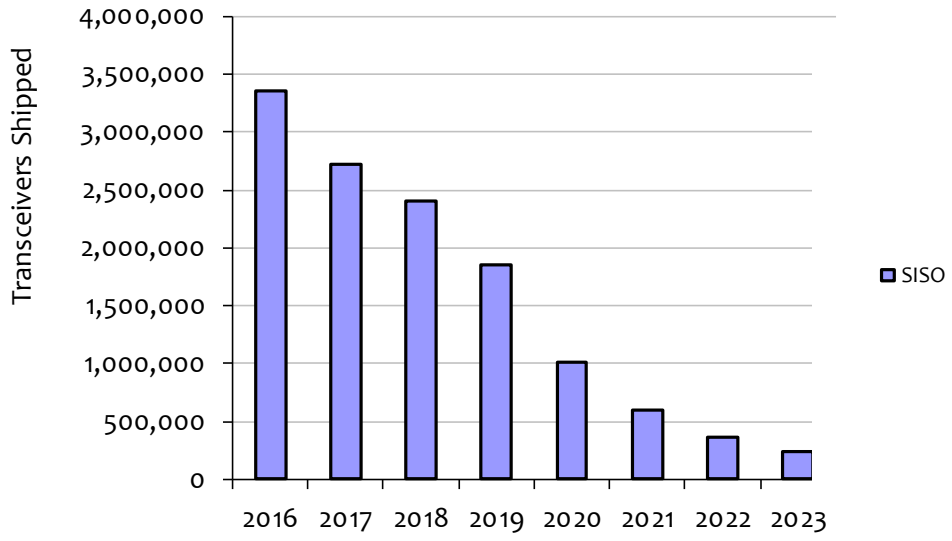
- MIMO: Mobile Experts refers to MIMO operating modes as M x N, (2x2, 4x2, 4x4, etc), where M is the number of RF transmitters and N reflects the number of RF receivers. Antenna diversity with a shared receiver, and antenna diversity with an identical transmitter signal from two antennas are not considered MIMO. In a Massive MIMO configuration, the number of MIMO streams is best kept to ¼ the number of transceivers, for spatial separation between beams. Recent TD-LTE upgrades involve 64T/64R radios but 16 MIMO streams in most cases.
- Transceiver Complexity: A 2T/2R radio includes two transceivers and two receivers. Recent deployment includes 64T/64R arrays, with 64 actual transceiver paths and receiver paths that can be combined in software for various levels of MIMO or beamforming. Note that recent systems use 128 antenna elements, with a 64T/64R radio, meaning that each radio drives two passive antenna elements (one in each polarization).
- Beamforming: In theory, each antenna element can be set to a different phase for precise beam steering. In practice, a large array would require huge processing resources, so the beamforming array is limited to 16 elements despite the availability of 128 antenna elements in recent Massive MIMO systems. This means that 16 groups, of eight antenna elements each, transmit at a specific phase in order to steer the beam.
- MIMO Streams: The number of separate MIMO streams is always lower than the number of antenna elements (the rule of thumb is a maximum of one MIMO stream for every 4 antenna elements in a beamsteering configuration)

Note: The Mobile Experts macrocell forecast is based on the adoption of MIMO technology in the downlink only. Separate forecasts illustrate the slower adoption of MIMO technology in the uplink, where handset battery limitations are a major factor.

SISO Forecast

All 2G and 3G base stations are deployed with SISO, despite the availability of 2x2 MIMO for HSPA. This market also includes NB-IoT, which has very quickly become the majority of the SISO market. We expect this segment to cool off significantly after the initial surge of NB-IoT deployment in China.

Chart 19: Forecasted SISO Transceiver Shipments, 2016-2023

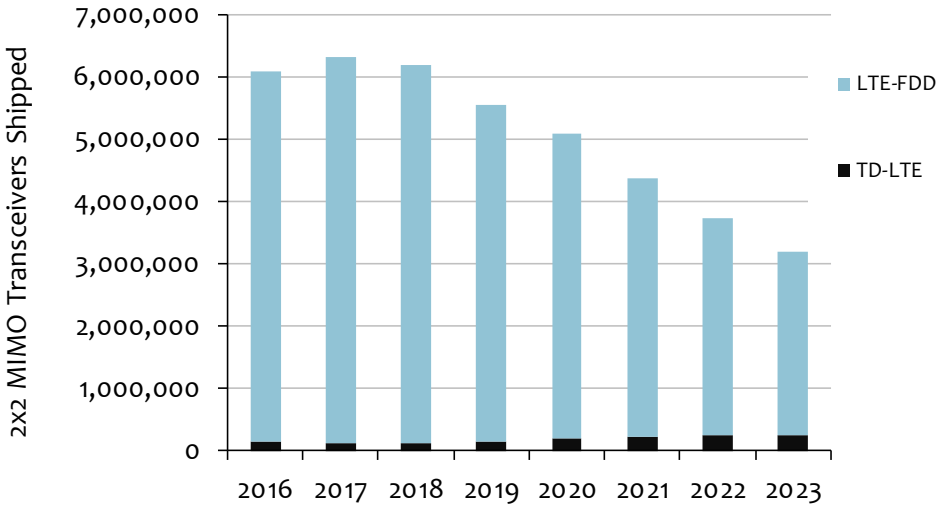


Source, Mobile Experts

2x2 MIMO Adoption

Initial LTE deployments between 2010 and 2016 utilized 2x2 MIMO as the main format, and many base stations currently in the field will stay in this configuration. Future growth will be in higher MIMO rank, so shipments at this level will flatten out.

Chart 20: Forecasted 2x2 MIMO Transceiver Shipments, by air interface, 2016-2023



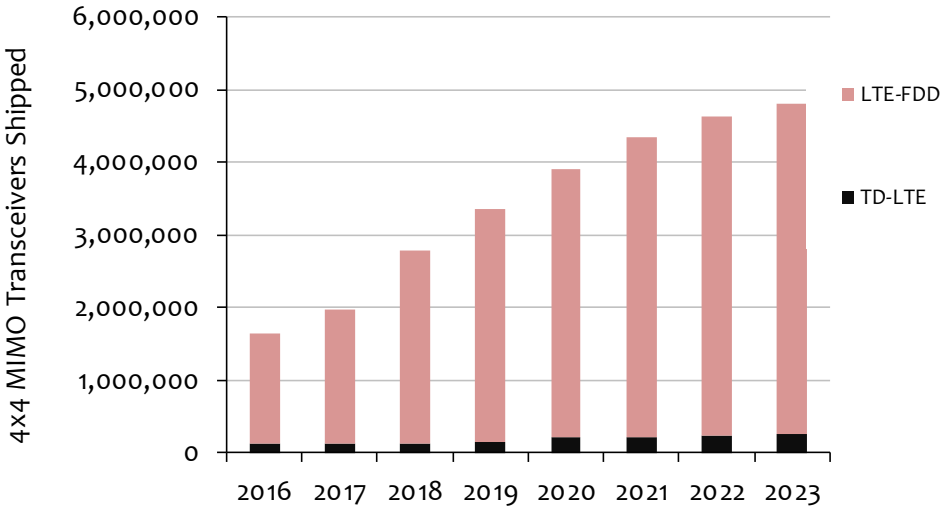
Source, Mobile Experts

4 x n MIMO Adoption

The 4T4R configuration has now become the standard setup for FDD-based LTE systems, and we expect that for any 5G NR in the FDD bands this configuration will also be the primary product setup. Handsets with 4-way MIMO in the high bands are on the market now, so the game has been elevated to a new level.

At low frequency bands (600-1000 MHz), 4x4 MIMO is not possible for handset form factors today. The implementation of 4x4 MIMO is limited by the size of the terminal at these frequencies, so most of our forecast represents the market between 1700MHz and 2.7 GHz.

Chart 21: Forecasted 4xn MIMO Transceiver Shipments, by air interface, 2016-2023



Source, Mobile Experts

8 x 8 MIMO Adoption

We still don't see any serious development programs underway for 8x8 MIMO implementation, with 8 receivers on a handset or other terminal. Counting the number of antennas in a CPE or a smartphone may give a different answer, but in terms of the number of active receivers we still do not see any activity for this level of MIMO to a single device.

Mobile Experts will continue to track the market for 8x8 MIMO, but for now the forecast for this specific implementation is zero.

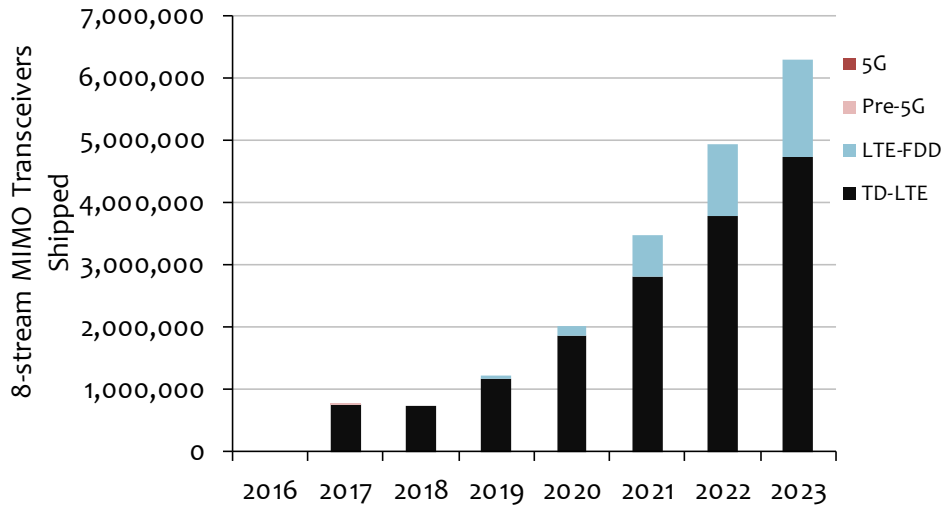
Multi-User MIMO (8-stream, 16-stream, and higher)

Through the use of Multi-User MIMO (MU-MIMO), multiple MIMO streams can be used to boost capacity, by re-using resource blocks for two users within the same sector. This only works if there's a way to isolate the two users well enough to avoid interference. In a practical sense, this means that beamforming is necessary.

In a simple example, a 64T / 64R array can support 16 MIMO streams, so if handsets support 4x4 MIMO, then in theory four users can enjoy 4x4 MIMO performance, essentially quadrupling the capacity of the sector by breaking it into four "sub-sectors" spatially.

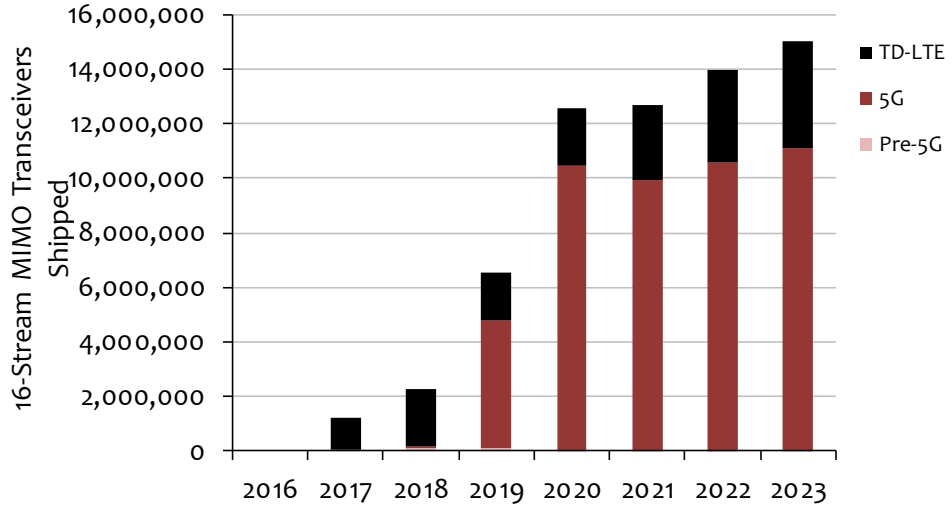
The following charts are shown as a forecast of the number of transceivers supporting each level of MIMO streaming. This is a very rough proxy for the level of capacity on the market using each level of MU-MIMO.

Chart 22: Forecasted 8-stream MIMO Transceiver Shipments, by air interface, 2016-2023



Source, Mobile Experts

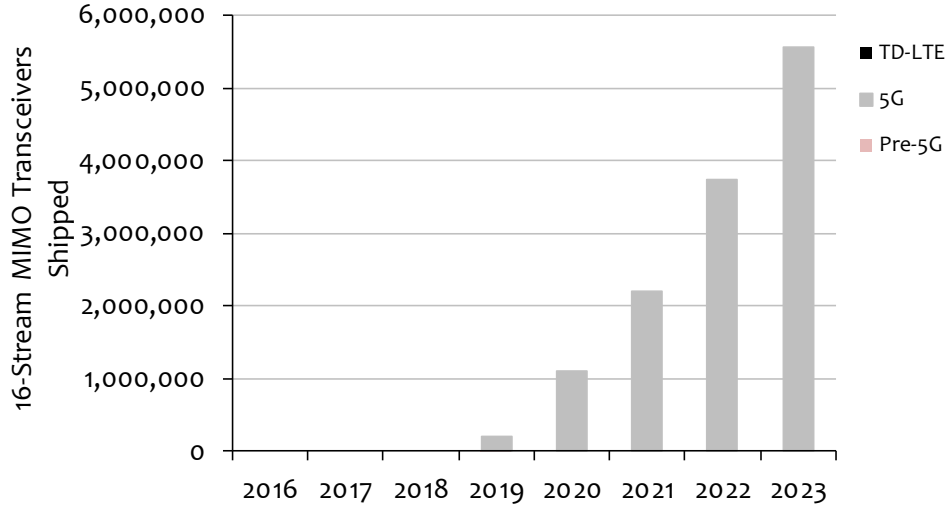
Chart 23: Forecasted 16-stream MIMO Transceiver Shipments, by air interface, 2016-2023



Source, Mobile Experts

Anybody want 24 or more MIMO streams per sector? This extreme level is likely in fixed-wireless applications and a few mobile sites….this tentative forecast is an estimate of how the ultra-high configurations will enter the market.

Chart 24: Forecasted 24-or-higher-stream MIMO Transceiver Shipments, by air interface, 2016-2023



Source, Mobile Experts

SECTION 4: REMOTE RADIO HEAD (RRH) FORECAST

RRH Architecture

Most new base stations are constructed with a Remote Radio Head architecture… in 2017, 96% of base station deployment took place in this architecture, with a small portion of the market using the "compact BTS" approach with RRH and baseband processing together in the same box.

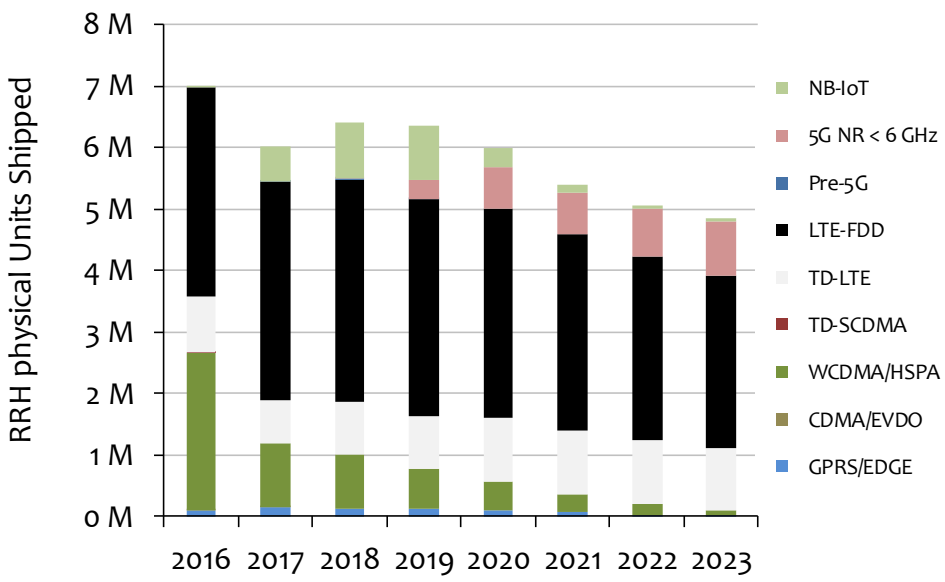
Note that Mobile Experts defines a macro RRH as a unit with 30W composite power or greater. Lower power remote radio heads are available, and in fact many have been shipped into Asian markets. Mobile Experts tracks these lower power units in our Small Cells forecast.

RRH Forecast

It's well known that a "normal" base station has three RRH units to cover three sectorsThe number of physical RRH boxes. In fact this number is higher for centralized RAN architectures, where the number of RRH units can be 4 or 5 in each "base station" deployment, assuming that the "base station" deployment is defined by an increment of baseband processing capacity.

The definition of a "base station" is becoming murky, as many people define this in different ways. Mobile Experts presents the below RRH forecast to offer a very simple view of the market: How many physical radio boxes are deployed each year?

Chart 25: Physical Macro RRH Shipments, by air interface, 2016-2023



Source, Mobile Experts

During 2017, the number of RRH units shrank significantly in the 2G/3G/4G trend, but the market's drop was mostly offset by growth in NB-IoT radio shipments. Note that a NB-IoT radio head is much simpler and less expensive than a wideband LTE radio so from a revenue point of view this offset was not so effective.

For 2018, there are multiple new factors which contribute to the rise in RRH deployment:

- FirstNet deployment in the USA has begun with significant deployment of new RRH units. Along with FirstNet deployment at 700 MHz will be retrofit of base stations with multi-band RRH units at 2 GHz.
- NB-IoT continues at a strong pace in China.
- T-Mobile USA has begun an aggressive deployment of 600 MHz FDD base stations (using LTE now, but hopefully upgradeable to 5G NR when the standards are ready)
- Ongoing LTE capacity deployment continues in almost every LTE network, with second/third/fourth frequency bands built out to add capacity to existing LTE coverage worldwide.

Important notes:

- Pre-5G and 5G RRH units will generally consist of Integrated Antenna Radio units, including multiple radio paths and the associated antenna elements.
- NB-IoT upgrades are counted in the Mobile Experts forecast only if a radio hardware upgrade is required. Most NB-IoT deployment will be possible with

software upgrades, so the small numbers of RRH units shown here represent the physically upgraded units.

SECTION 5: AAS and IAR FORECAST

Active antenna systems have been explored for more than 20 years in the mobile market, but we have finally reached a point where the benefit outweighs the cost. For LTE and also for 5G NR, active beamforming can boost spectral efficiency dramatically, so we expect network hotspots with high traffic demand to use them.

TDD implementation is more straightforward, with "channel reciprocity" making the closed-loop operation of the radio link possible. Also, the TDD bands available have more RF bandwidth, and therefore there is more benefit to the higher spectral efficiency. With more bandwidth, every dollar invested turns into more capacity.

FDD systems are also coming along, and field trials are showing enough performance boost to justify upgrades to LTE sites. Because of narrower LTE bands in the FDD domain, we don't expect as much adoption of AAS.

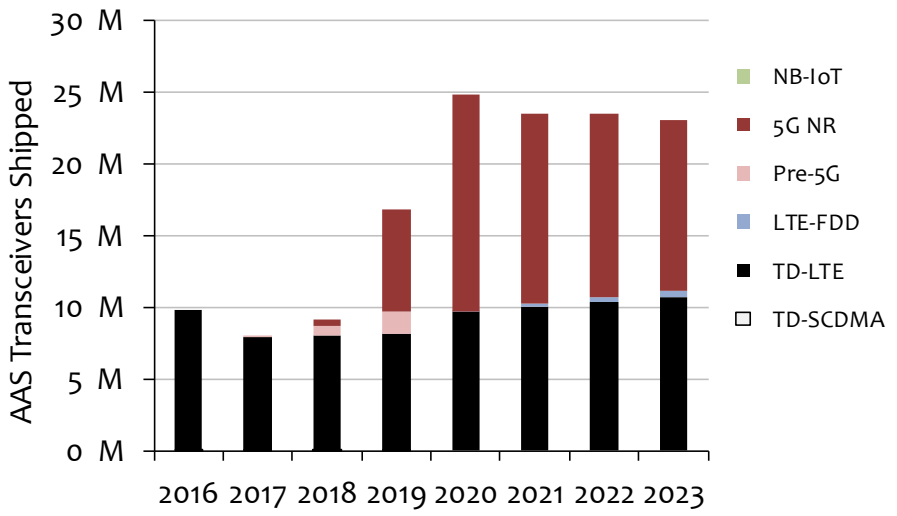
It's important to note that Active Antenna Systems and Integrated Antenna Radio systems are very different things. Active Antenna systems refer to beamforming with multiple antenna elements, and while this can be achieved without radio/antenna integration, the typical implementation of AAS is to integrate the two boxes. On the other hand, we have seen shipment of many Integrated Antenna Radio systems (the Ericsson AIR product) over the past few years without the use of beamsteering.

AAS Transceiver shipments

TD-LTE deployment drove AAS architectures into the mainstream, especially with the huge Chinese deployment of 2014-2015. These simpler implementations at 8T8R are now moving up to 64T64R and higher, for both TD-LTE and 5G NR.

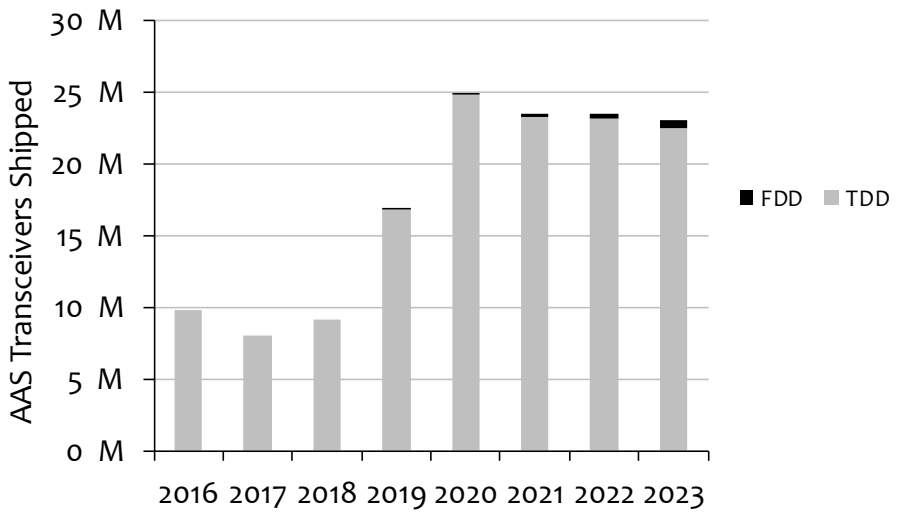
The higher complexity allows for tighter beams, and also for higher isolation between beams to improve the overall spectral efficiency. One tradeoff is that with many small power amplifiers, the total heat load of a large array can be higher than a simpler 4T4R radio head with four big amplifiers. This issue can be resolved by using the higher gain of the antenna to turn down the power.

Chart 26: Transceivers shipped in AAS configuration, by air interface, 2016-2023



Source, Mobile Experts

Chart 27: Transceivers shipped in AAS configuration, TDD vs FDD, 2016-2023



Source, Mobile Experts

5G NR will quickly take the lead in terms of the capacity deployed in the AAS architecture. While we will have ongoing deployment in both TD-LTE and LTE-FDD, we expect China's deployment of 5G NR at 3.5 GHz to drive huge numbers of AAS sectors, as early as 2019.

Integrated Antenna Radio shipments

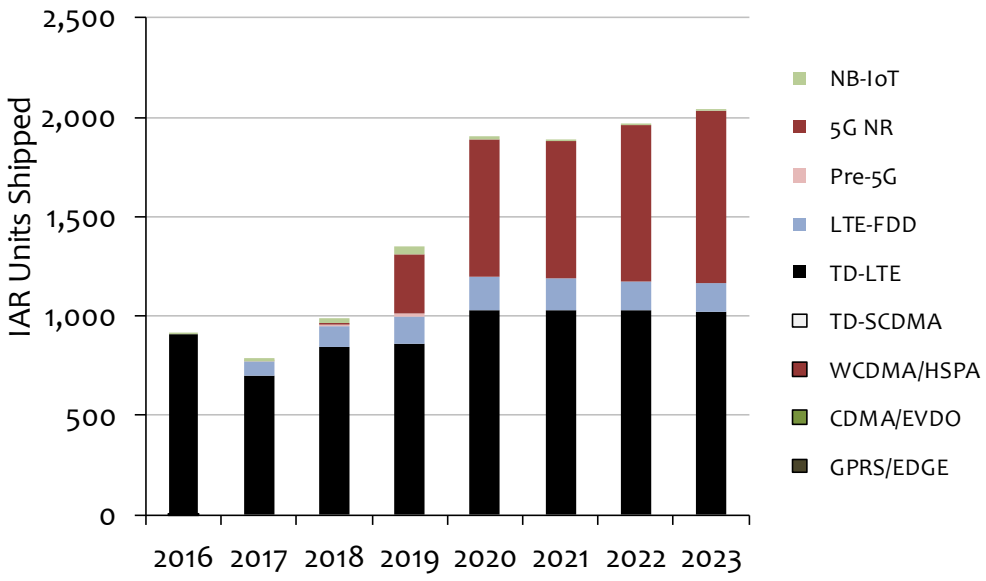
The Integrated Antenna Radio configuration involves the physical integration of the antenna and the RRH electronics, regardless of whether a beamsteering array is used. This concept has been used by Ericsson with customers such as T-Mobile, SMART, and a few other operators in the FDD market, as well as the more obvious cases with TD-LTE systems.

In the FDD market, IAR products have not been very popular, because the flexibility of the solution makes it impossible to upgrade the IAR for additional bands or different power levels. For example, for T-Mobile to add the 600 MHz band to the antenna would be easier without the IAR deployment, because the RRH could have remained in place at the existing LTE band, with a new multi-port antenna taking care of the existing RRH as well as the new 600 MHz RRH.

Ericsson has modified the AIR product to include "field replaceable units" that plug into the antenna chassis with blind-mate connectors. This change is a big improvement, because it allows for smaller size/weight in each physical unit, and it allows for upgrade of the hardware in the future without taking down the entire assembly. Long term adoption of this is still unknown.

For 5G radios, we expect widespread use of the integrated antenna/radio concept, in order to reduce electrical loss between the radio and the antenna. Multi-band implementation has been demonstrated by some vendors, but it's not clear whether this will be used in the field. There certainly will be strong pressure to integrate 2.5 and 3.5 GHz antenna arrays, although it may be difficult to have so many amplifiers on a single heat-sink.

Chart 28: Integrated Antenna Radio Shipments, by air interface, 2016-2023



Source, Mobile Experts

SECTION 6: TRANSCEIVER FORECAST BY POWER LEVEL

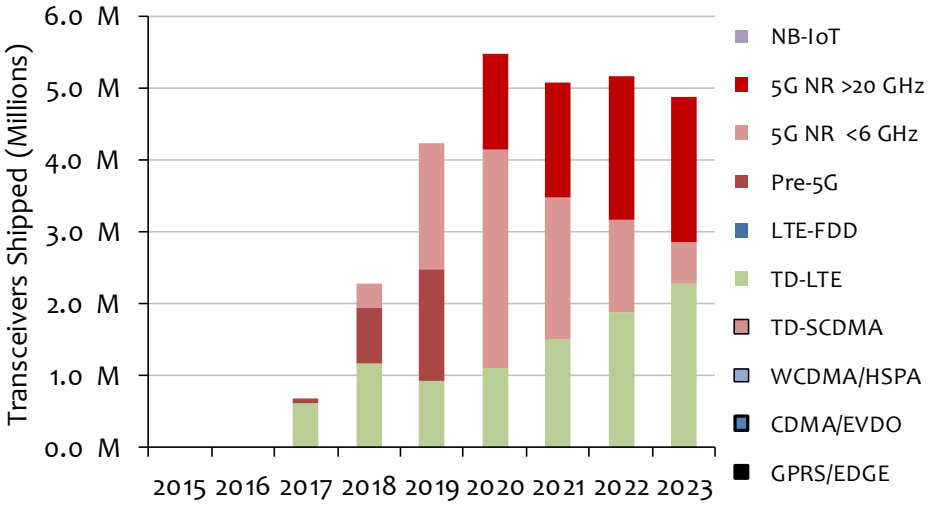
From 2G to 3G and 4G, the clear trend is to higher numbers of transceivers in each sector, with lower power in each radio transceiver. The old days of 100 W amplifiers booming across the countryside are over… now, we have 4x40W LTE transceivers as a standard configuration. The power level is about the same in the end, but with MIMO the radios are built differently.

Mobile Experts defines a macrocell as a mobile infrastructure site in which a radio sector transmits a composite rated power of 30W or more. In each sector, the total power of all diversity transmitters, MIMO transceivers and/or all AAS transceivers is calculated to determine the composite power. Systems with composite power between 5W and 29W in a sector are categorized as "microcells" and are not included in the scope of this forecast. To be clear, a 5G antenna array with 64 elements that transmits 60W of composite power (1W per element) is considered a macro system.

Very Low Power Transceivers (below 5W)

Massive MIMO systems with high numbers of transceivers (64T64R and higher) generally fall into this category. Growth is just taking off, and we expect a major jump in 2019-2020 as China's 5G deployment gets going. In China, we expect that a lot of the 2019-2020 deployment will involve 64T64R, and that after 2020 the Chinese operators will move outside of the urban center, using 8T8R systems instead. As a result, we have a surge of Massive MIMO and low power transceivers in the 2020 timeframe, and we're likely to see flatter shipments in 2021-2023.

Chart 29: Transceiver Shipments, Below 5W rated power, 2016-2023

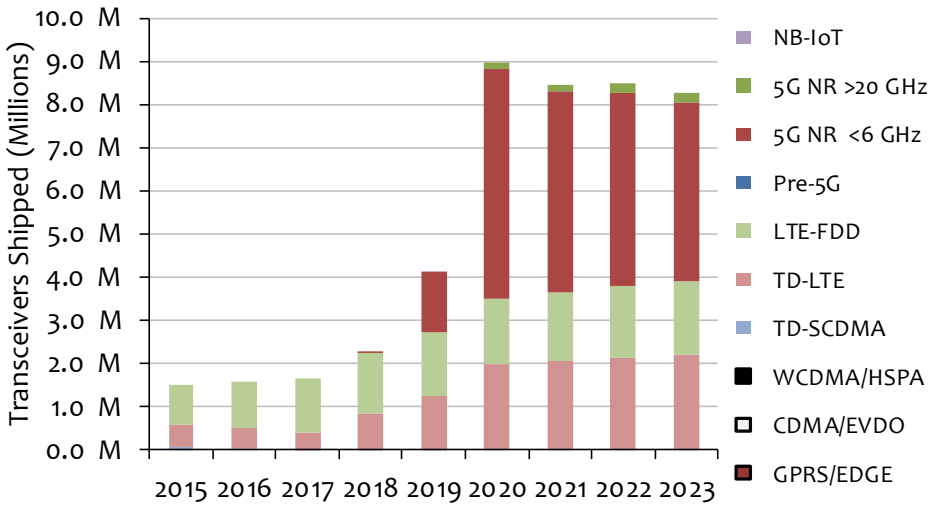


Source: Mobile Experts. Includes macro only (Base stations with greater than 30W composite power per sector)

Low Power Transceivers (5-19W)

Radios in 8T8R through 16T16R configurations often fall into this power level category, in between the Massive MIMO extreme and the traditional 2T and 4T systems. In China, we're predicting that about 20% of the 5G network will use a 16T16R configuration, so there should be solid shipments of this type of radio in the 2020-2023 timeframe.

Chart 30: Transceiver Shipments, 5-19W rated power, 2016-2023

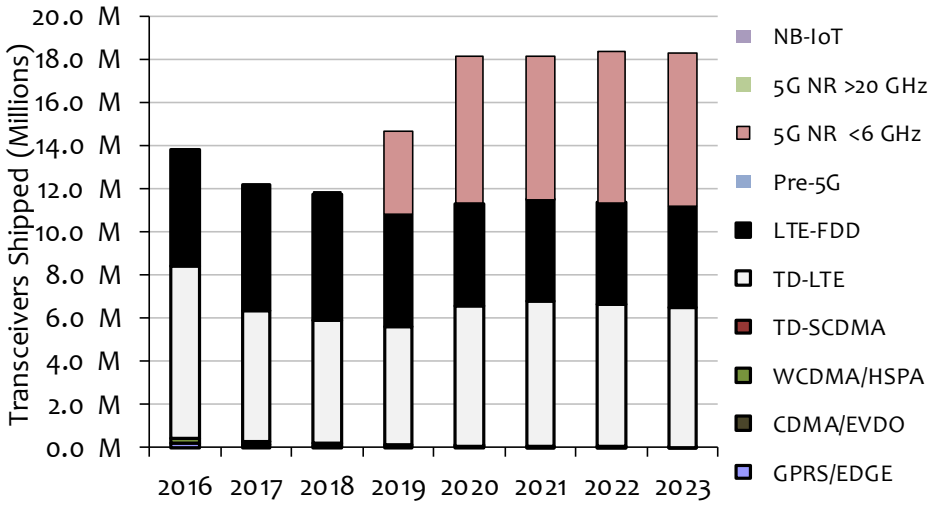


Source: Mobile Experts. Includes macro only (Base stations with greater than 30W composite power per sector)

Transceivers rated at 20-40W

Most macro base stations are used primarily for coverage, not capacity….so large numbers of base stations are expected to use 4T4R or 8T8R configuration, even in 5G NR deployments. This moderately high power radio segment will continue with solid LTE shipments through 2023, plus a portion of the 5G shipments in the sub-6GHz bands.

Chart 31: Transceiver Shipments at 20-40W rated power, 2016-2023



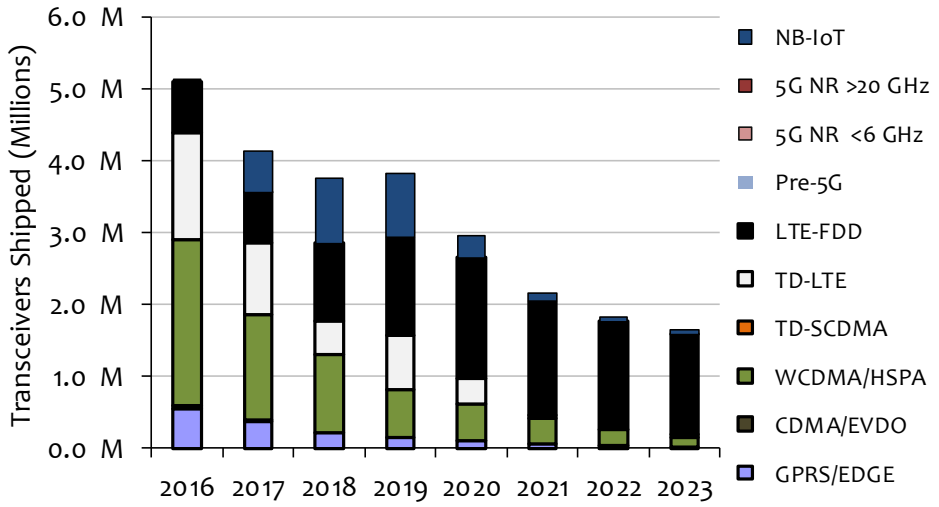
Source: Mobile Experts

Transceivers above 40W

The old days of "Tower and Power" are over, but we still see plenty of systems with 2x60W or 2x80W shipping for LTE in the FDD bands. This configuration will decline over time, as 4x40W replaces the 2x80W configuration… but this is still the most economical way to get coverage if capacity is not an issue.

The IoT market will drive some growth in the high-power radio market. Almost all upgrades to LTE systems for NB-IoT will use high power radios, in a 1T2R configuration.

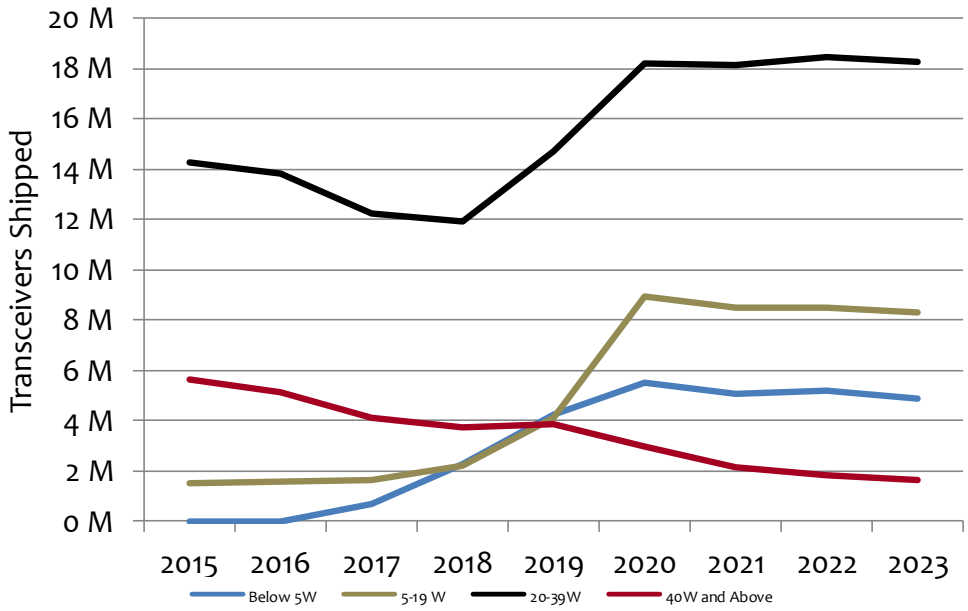
Chart 32: Transceiver Shipments above 40W rated power, 2016-2023



Source: Mobile Experts

Looking at the overall picture, clearly the mid-power transceivers are increasing in prominence while the higher power radios are declining. The lowest tier, below 5W, is rising from zero to become a significant portion of the market.

Chart 33: Transceiver Shipments by rated power level, 2015-2023



Source: Mobile Experts

SECTION 7: TRANSCEIVER SHIPMENTS BY REGION

As LTE deployment settles in, we find that the big surge in China/USA/Korea/Japan is finished, but operators worldwide are continuing with LTE deployment to fill in the capacity of the network. At the same time, we have a few regions that will dominate the 5G deployment in the 2019-2023 timeframe: China in particular will represent two thirds of the market for 5G equipment due to strong government support.

Countries with lower ARPU are still deploying LTE for the first time in many areas, so we expect the 5G deployment cycle to be focused on China, APAC, and USA for the next few years. Other regions will follow later.

Chart 34: Transceiver Shipments, by Region, 2016-2023

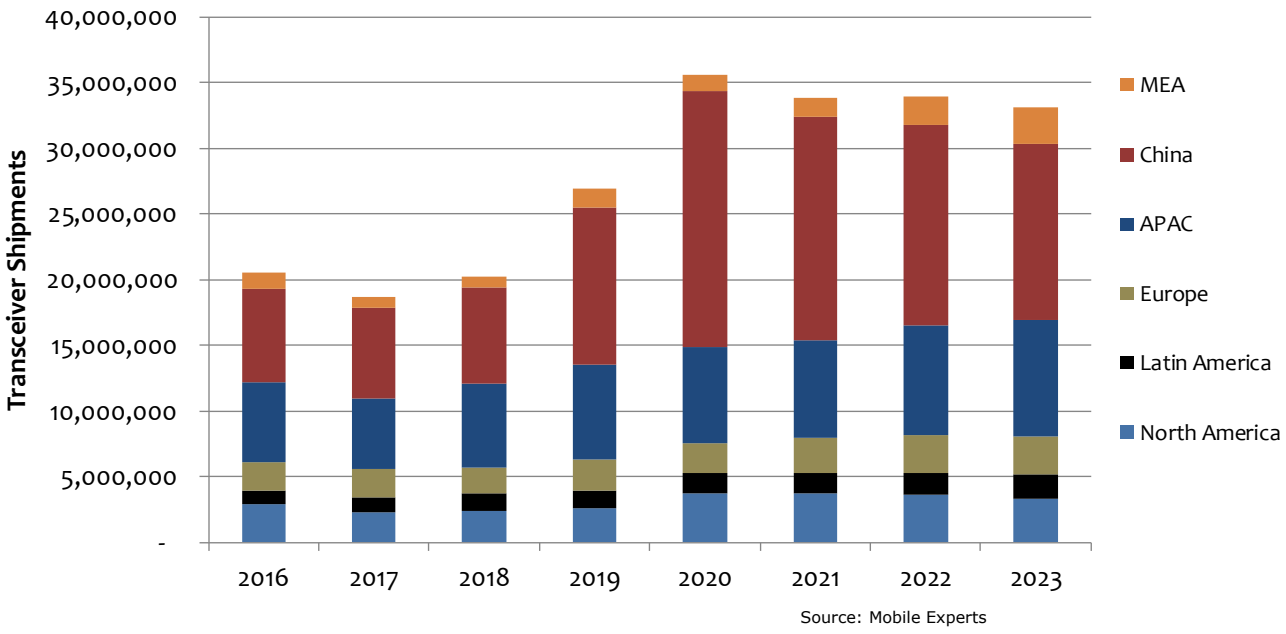
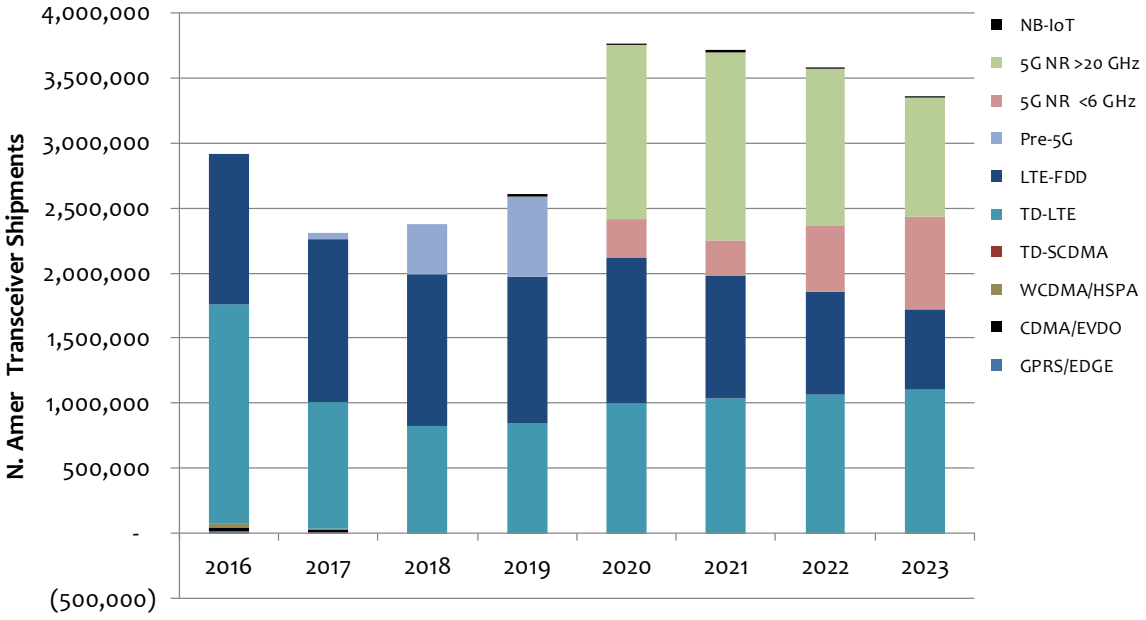
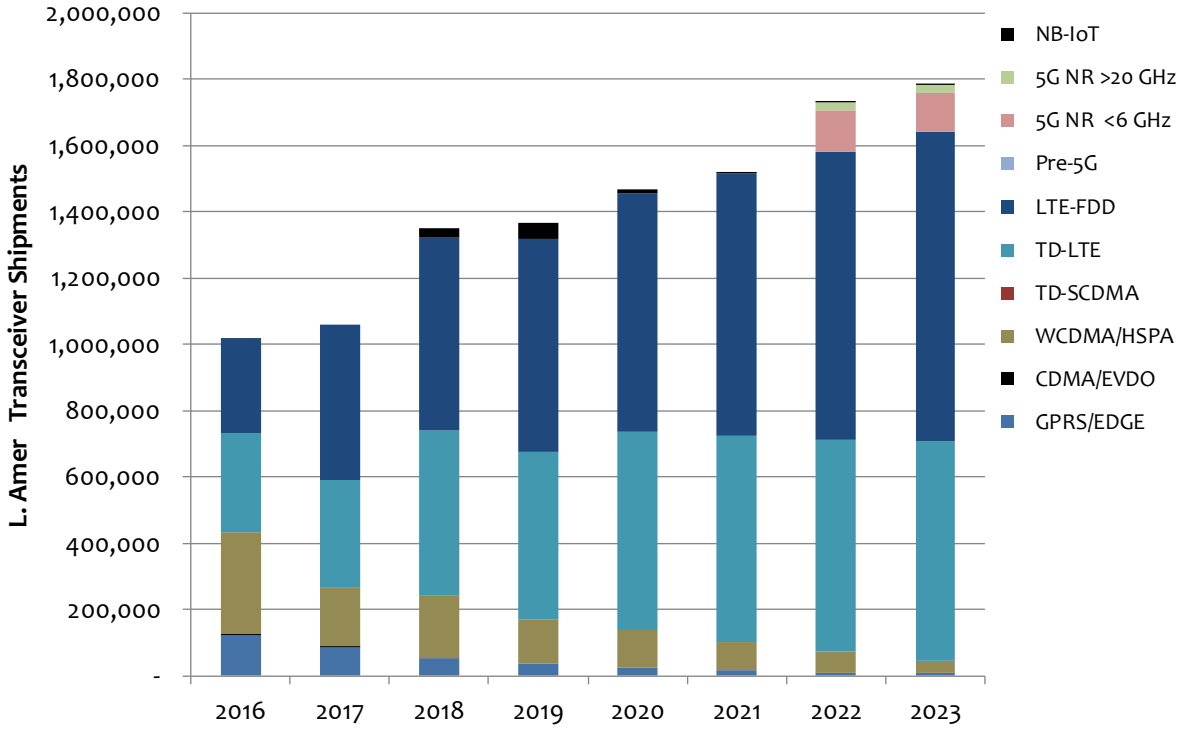


Chart 35: Transceiver Shipments, North America, by air interface, 2016-2023



Source: Mobile Experts

Chart 36: Transceiver Shipments, Latin America, by air interface, 2015-2023



Source: Mobile Experts

Chart 37: Transceiver Shipments, Europe, by air interface, 2016-2023

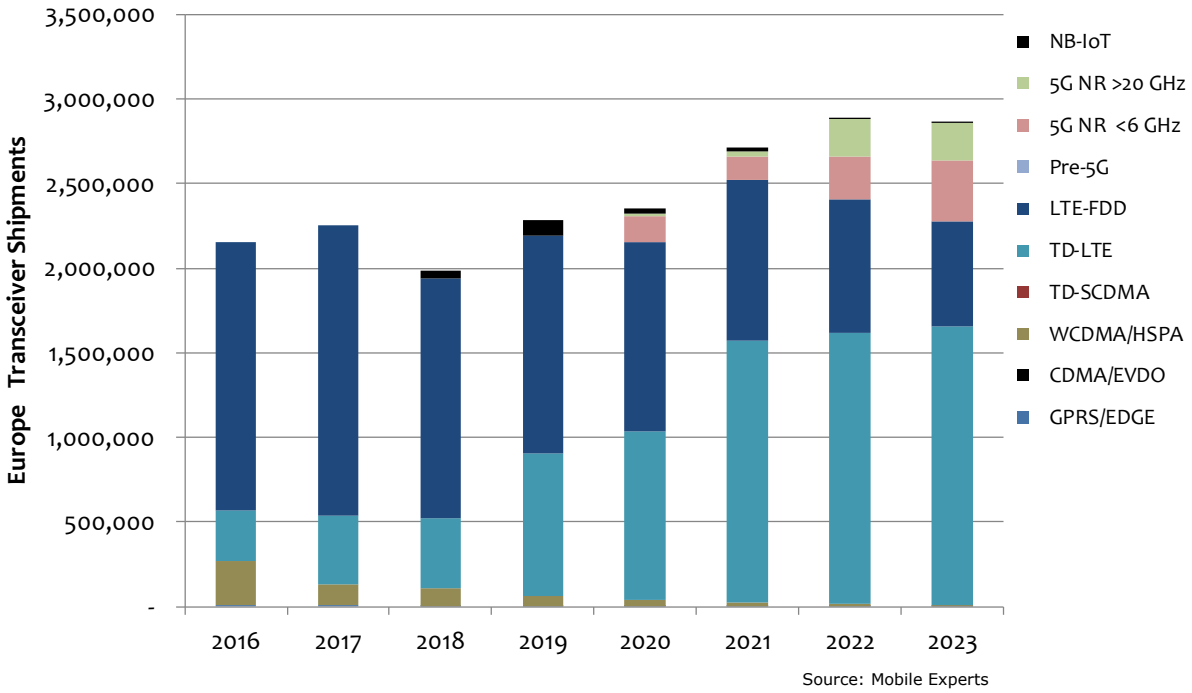


Chart 38: Transceiver Shipments, APAC, by air interface, 2016-2023

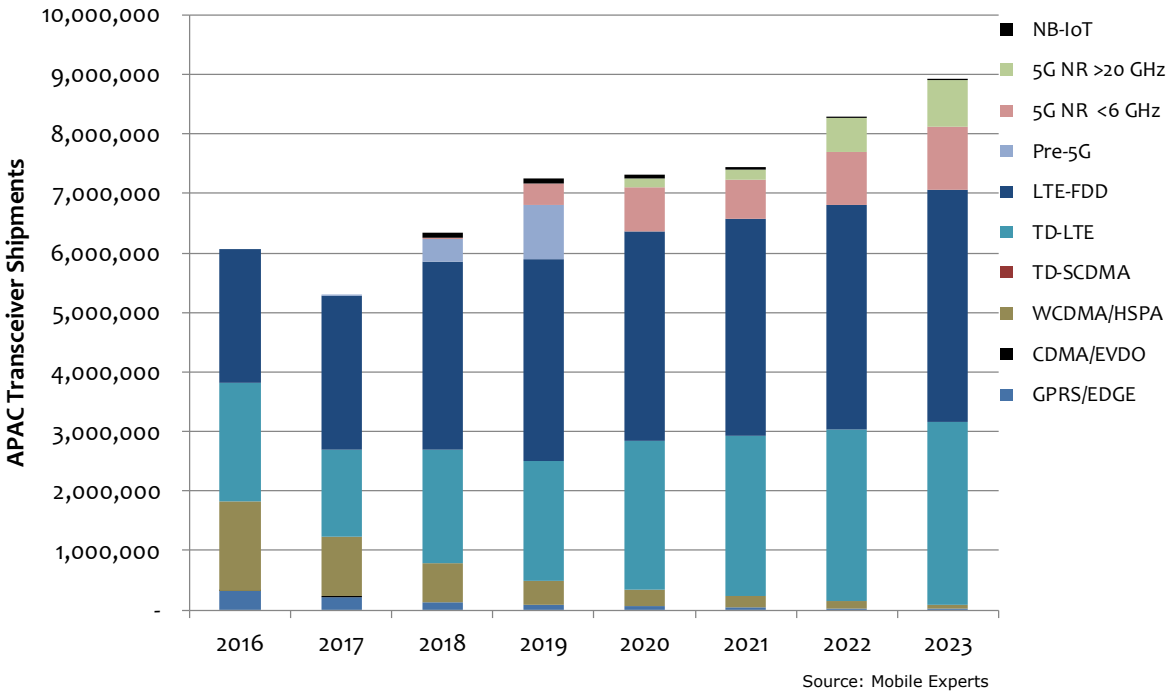


Chart 39: Transceiver Shipments, China, by air interface, 2016-2023

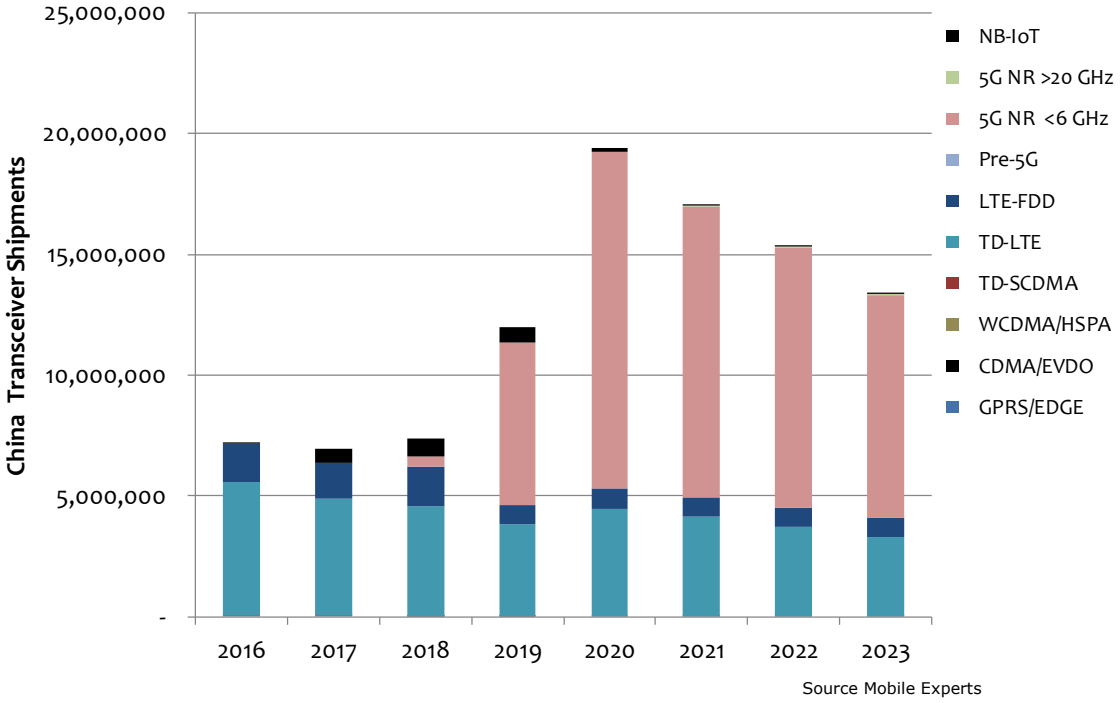
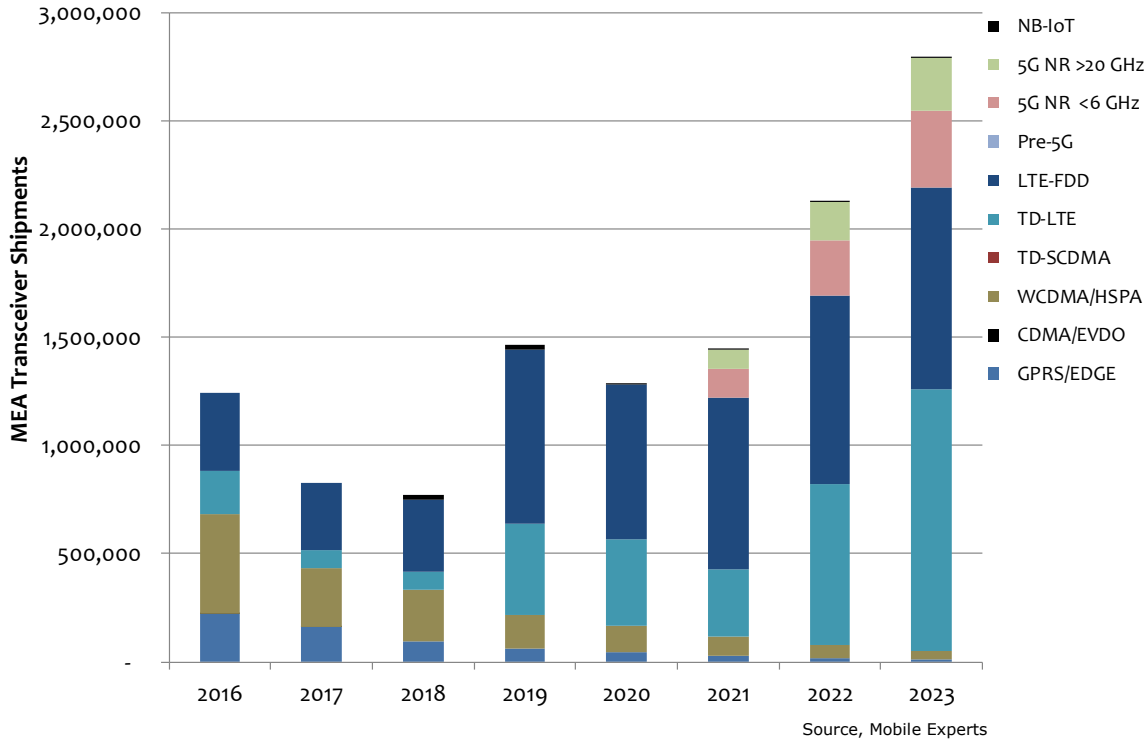


Chart 40: Transceiver Shipments, MEA, by air interface, 2016-2023



SECTION 8: TRANSCEIVER SHIPMENTS BY OEM

Competition in the mobile telecom market has been difficult, and only big companies survive in this market. Huawei and ZTE now ship more radios than their Western competitors—by a wide margin. Nokia remains strong in terms of revenue and profitability, due to strength in software and services. Ericsson is restructuring, to reset their company as their reliance on RAN deployment leaves the company starved for revenue during the past year.

Methodology for estimating shares

Shipment shares are estimated based on the contract awards announced and by public financial disclosures by each of the major OEMs. These figures were double-checked against shipment data for key components.

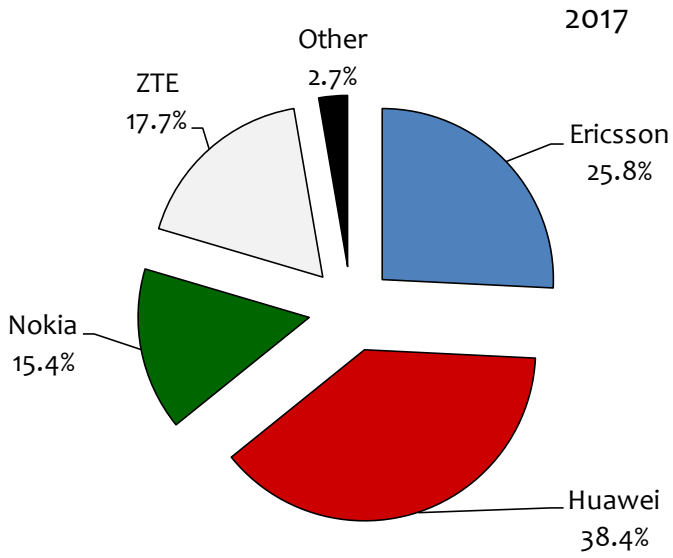
Important note: Mobile Experts does not track traditional "market share" for the base station market. Most analysts include base station site hardware and software revenue, as well as service revenue in many cases. The result is not meaningful to the hardware supply chain.

The Mobile Experts forecast does NOT address revenue share. Instead, the Mobile Experts forecast focuses simply on the share of RF transceivers shipped by each vendor, in order to best estimate the market for semiconductor suppliers. Revenue for the transceivers is not considered because the "pricing" of a transceiver is arbitrary. The below estimates reflect the number of transceivers shipped in order to most directly relate to the component market.

Market Share Charts by Air Interface Standard

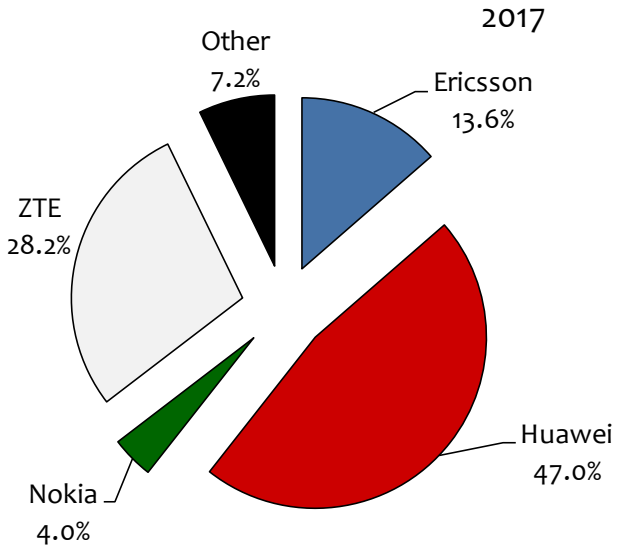
The following charts show share of transceiver shipments for calendar 2017:

Chart 41: Overall Transceiver Shipment Shares, by OEM, 2017



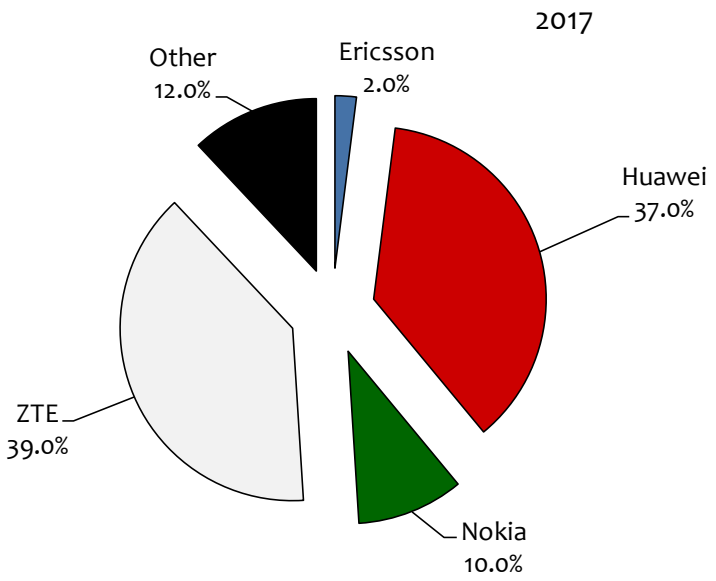
Source: Mobile Experts

Chart 42: GSM/EDGE Transceiver Shipment Shares, by OEM, 2017



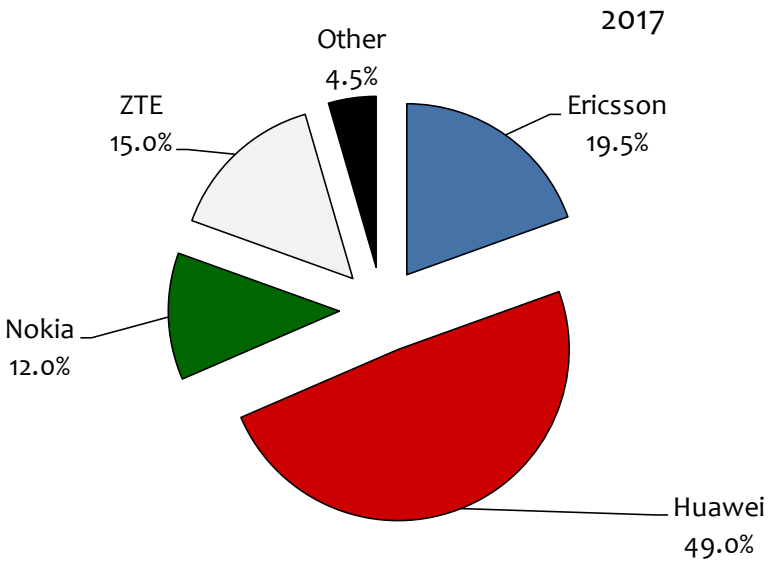
Source: Mobile Experts

Chart 43: CDMA/EVDO Transceiver Shipment Shares, by OEM, 2017



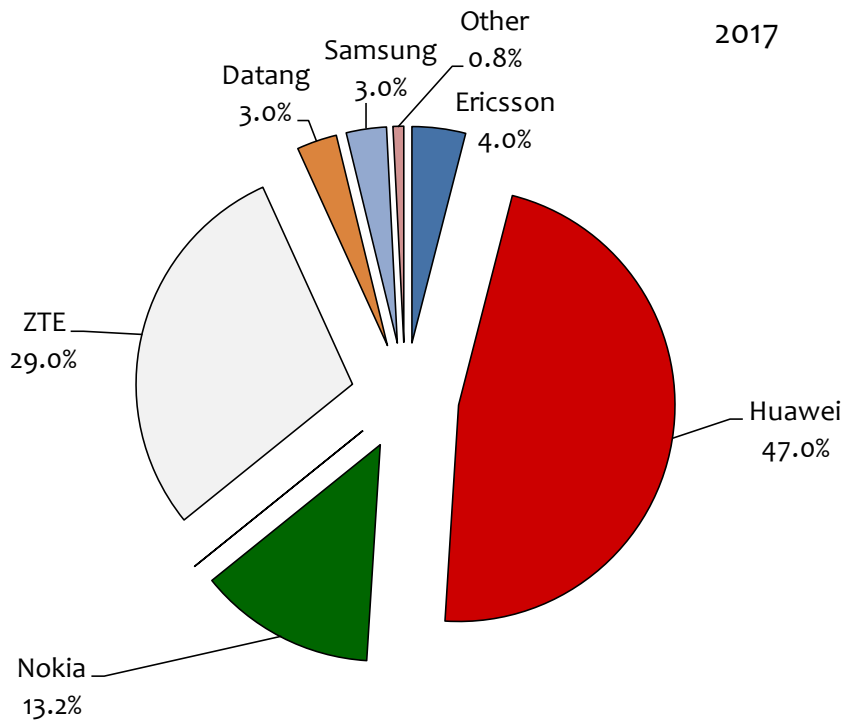
Source:, Mobile Experts

Chart 44: WCDMA/HSPA Transceiver Shipment Shares, by OEM, 2017



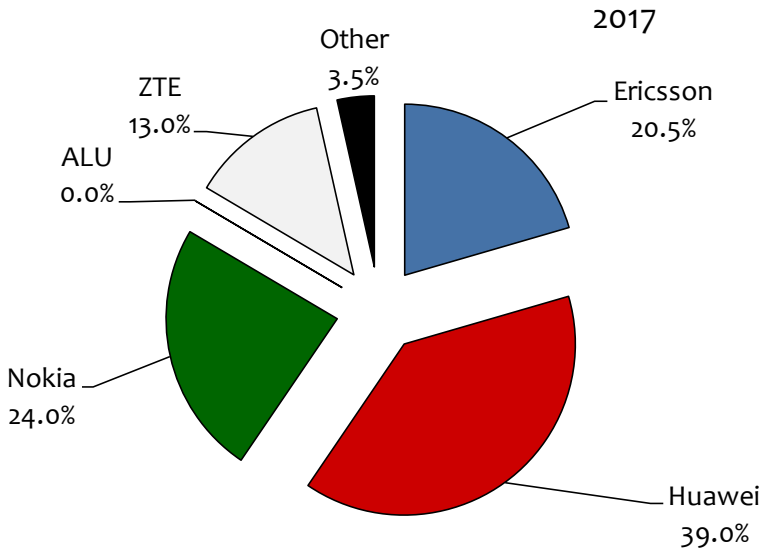
Source: Mobile Experts

Chart 45: TD-LTE Transceiver Shipment Shares, by OEM, 2017



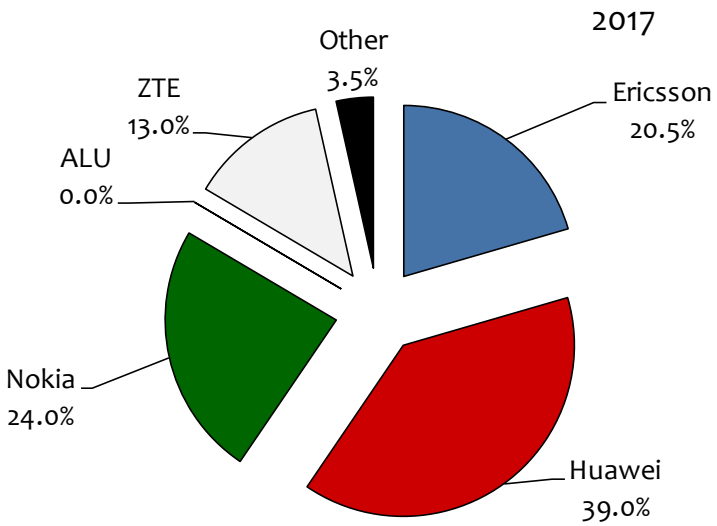
Source: Mobile Experts

Chart 46: LTE-FDD Transceiver Shipment Shares, by OEM, 2017



Source: Mobile Experts

Chart 47: NB-IoT Transceiver Shipment Shares, by OEM, 2017



Source: Mobile Experts

SECTION 9: DEFINITIONS AND METHODOLOGY

To create estimates and forecasts for Macro Network equipment shipments, Mobile Experts relied on direct input from at least 28 industry sources, with 30 different mobile operators contributing to the overall analysis to give a detailed global view of the market. Mobile Experts built a "top down" forecast based on direct input from mobile operators and based on trends in end-user demand for mobile services and specific plans for base stations. Then, Mobile Experts built a "bottom up" forecast through discussions with the supply chain. Notably, multiple key semiconductor suppliers have been willing to share shipment data with Mobile Experts, to confirm our shipment figures for 2017 and backlog estimates for 2018. Mobile Experts also used financial disclosures from publicly traded companies to confirm our quantitative view of the equipment market.

Mobile Experts defines the macro base station market with strict technical criteria, to keep it separate from the small cell and DAS equipment markets. Specifically, radio equipment is counted in the "Macro" category if the composite power for a sector exceeds 30W. In this definition, macro base stations may be omnidirectional, or sectorized. The transceivers counted in this study include transceivers in active antenna arrays (AAS), in remote radio heads (RRHs), and integrated into base station cabinets.

A "base station" is defined as the equipment supporting a single Macro site: typically one or more baseband processing units, three Remote Radio Heads, plus cabling, antennas, power supplies, and other equipment. Each "base station" covers one frequency band, so that multiple "base stations" are co-located on a site. Note that with the Centralized RAN architecture, the term "base station" is not as useful as it was in the past. We use "transceivers" as our primary metric.

A Transceiver is defined as a physical radio transmitter path and all of the receivers that are related, including the main receiver, diversity, sampling, and sniffing receivers. To be clear, a 64T64R radio box contains 64 transceivers. A 1T2R radio box contains one transceiver, despite two receivers for diversity.

A Remote Radio Head is defined as a physical box which converts a digital I/Q data stream into transmitter and receiver signals and boosts the transmit signal to the desired power level. A base station is considered to use the RRH architecture if CPRI, OBSAI, ORI, or any similar serial I/Q data stream is utilized between baseband processor and radio unit.

Market shares are listed as the share of transceiver shipments in all cases, not as the share of revenue. Base station revenue is priced as a combination of hardware, software, and services, so the revenue associated with hardware is arbitrary, and traditional definitions of "base station market share" are meaningless. Therefore Mobile Experts simply reports the share of transceiver shipments that we track through component vendors and operator inputs.

North America:	USA and Canada
Latin America:	Mexico through South America, including Caribbean
Europe:	Western and Eastern Europe, including Russia
China:	China, including Tibet and Hong Kong
Asia Pacific:	India through Australia/Micronesia, excluding China
Middle East/Africa:	Pakistan and Turkey through Africa
Multimode:	Capable of multiple simultaneous air interface standards (LTE, HSPA, GSM, etc)
Adaptable:	Capable of one air interface standard at a time, but reprogrammable
Single-mode:	Capable of only one air interface standard
Multiband:	Capable of operating in multiple frequency bands, one at a time
Carrier Aggregation Units:	Units which operate in multiple bands simultaneously

Figure 2. Key defnitions for regions and transceiver types

Source: Mobile Experts

Base Station:	A set of equipment which performs baseband processing to support mobile radio transmissions above 30W composite power, including BTS, nodeB, and enodeB types. NOTE: A Base Station Shipment can include a physical base station or simply a software upgrade so this metric can be misleading.
Transceiver:	An electronic assembly including transmitter (from DAC to modulated output) and one or more receiver chains (from antenna input to ADC). E.g. A 2x2 MIMO channel uses two transceivers at the base station. A 64T/64R radio refers to a radio with 64 transmitters and 64 receivers, or 64 transceivers overall.
MIMO:	In this forecast MIMO is categorized according to downlink configuration. MIMO order is designated by n x m, where n=number of transmit antennas and m=number of receive antennas.
M-MIMO:	Massive MIMO: In general this refers to MIMO with more than 8 transmitting elements.
MU-MIMO:	Multi-User MIMO: The use of multiple available MIMO streams with a subset of the MIMO streams devoted to individual users or groups of users to optimize overall capacity
AAS:	Active antenna systems refer to beamsteering systems, with multiple antenna elements transmitting the same signal, phased for beamsteering control.
CA:	Carrier Aggregation, in this forecast, refers to inter-band Carrier Aggregation and not to Intra-Band Carrier Aggregation.
Ultra High Density:	Traffic density above 100 Mbps/km2/MHz
High Density:	Traffic density above 20 Mbps/km2/MHz
Mid Density:	Traffic density between 5 Mbps/km2/MHz and 20 Mbps/km2/MHz
Low Density:	Traffic density below 5 Mbps/km2/MHz
GkM:	Gbps per square kilometer per MHz of licensed spectrum. Includes uplink and downlink traffic but not Wi-Fi traffic
MkM:	Mbps per square kilometer per MHz of licensed spectrum. Includes uplink and downlink traffic but not Wi-Fi traffic.

Figure 3. Key defnitions for other terminology

Source: Mobile Experts